

NIST Technical Note 1291

Fire Performance of Wire and Cable: Reaction-to-Fire Tests-A Critical Review of the Existing Methods and of New Concepts

***Vytenis Babrauskas, Richard D. Peacock, Emil Braun,
Richard W. Bukowski, and Walter W. Jones***

**United States Department of Commerce
Technology Administration
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December 1991



U.S. Department of Commerce
Robert A. Mosbacher, Secretary
Technology Administration
Robert M. White, Under Secretary for Technology
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John W. Lyons, Director

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Corrections to NIST TN 1291

Subsequent to the publication of NIST TN1291, it was learned that the business relationships between FMRC and industrial property insurers, and the background and intended audience for the FMRC test had been incorrectly reported. Accordingly, section 3.4 on pages 28-31 of the report should be replaced with the following.

3.4 FMRC Tests

As we discuss later, there is a growing consensus within the fire community that HRR-based testing for electric cables is the best way to obtain usable data on cable flammability. Factory Mutual Research Corporation (FMRC) was one of the pioneers of developing laboratory and large-scale methods for HRR testing. We discuss this early FMRC work together with other HRR studies later in this report. In this section, we discuss the test method which FMRC is currently using.

In 1987 FMRC summarized the flammability provisions of the NEC and pointed out that a different, mutually incompatible, rating system could also be devised [269]. Unlike most testing organizations, FMRC is in a unique position since their findings are used by a field engineering organization owned by three industrial property insurers. FMRC is an independent entity which can promulgate fire tests which have a wide-ranging impact. FMRC also functions as a testing, labeling, and certifying laboratory.

As described in the HRR section below, much FMRC testing is done according to standard engineering principles of making HRR measurements, similar to such testing now conducted at more than a hundred laboratories that contain one type or another of bench-scale HRR apparatus. During FMRC's development of the cable test standard a number of industry concerns were expressed [63] which were never completely resolved. The test evolved from a HRR test into a scale model cable test combined with a standard test measuring a thermal inertia/ignition temperature parameter. Apparatus to perform the scale-model-type test is only available at two other USA locations (UL, David Taylor Research Center) and at about a half-dozen European locations (France, Germany and UK).

This FMRC standard was published in 1989 as Specification Test Standard - Cable Fire Propagation (Class Number 3972). The test has two Phases. In Phase 1, a single piece of cable, 127 mm long, is placed horizontally on the load platform of the test apparatus and is exposed, progressively, to various specified irradiances. In this Phase an irradiance vs. time to ignition curve is produced. Unlike most testing in heat release rate apparatus a designated specimen holder is not filled with lengths of specimen; rather, only a single specimen length is exposed. A Thermal Response Parameter is obtained by plotting the data of ignition time (t_{ig}) versus the irradiance (q_e) as:

$$t_{ig}^{-1/2} = \frac{\dot{q}_e''}{\Delta T(k\rho C_p)^{1/2}} - a \quad (1)$$

where $\Delta T(k\rho C_p)^{1/2}$ is the Thermal Response Parameter (TRP).

In Phase 2, a single piece of cable 0.61 m long is mounted vertically in the apparatus. A horizontal plane irradiance of 50 kW/m² is set near the bottom of the specimen. The upper portions of the specimen, of course, see a sharply smaller or zero irradiance. In this Phase, the combustion atmosphere supplied is

at 40% oxygen. The heat release rate is measured over a specimen which is undergoing flame spread and being subjected to almost uniform external heating over a small section (less than 10%) at its lower end. A Fire Propagation Index (FPI) is then computed as:

$$FPI = \frac{[0.40 \dot{Q}_{chem}/\pi D]^{1/3} \times 10^3}{TRP} \quad (2)$$

where \dot{Q}_{chem} = HRR (kW), and D = the cable outer diameter (m).

Cable performance is then classified into one of three groups:

- Group 1: FPI < 10
- Group 2: 10 < FPI < 20
- Group 3: FPI > 20.

Technical analysis of the FMRC standard

° Elevated oxygen testing conditions

The use of an air stream containing 40% oxygen would appear on first blush as unreasonable for testing materials or products which are to be used in an environment where the oxygen concentration is 21% or less. Augmented-oxygen test conditions are reported to simulate the burning behavior of very large pool fires with diameters of several meters and heat release rates in megawatts [64]. As with all test methods, one must ask whether the scenario measures properties that are relevant to the situation to be standardized, then whether it is a sensible scenario, and finally, whether the pass/fail criteria are justified.

Since the FMRC scenario depends on flame spread and not HRR, a lab apparatus must simulate flame spread. Furthermore, as most of the products under consideration exhibit low flame spread, FMRC decided to use elevated oxygen conditions to stimulate flame spread in the test. Oxygen augmentation can affect the flames from different polymers in very different ways—compare, for instance, the data of Aseeva [65] for polypropylene, versus the data of Khalturinsky [66] on PMMA. Flame retardant systems will also vary greatly in their effect as the thermal environment is changed. The result of these effects will be a preferential bias for one type of polymer/FR-agent system, versus another. This is not desirable. What is needed is a moderate external flux to be imposed on the specimen, and no increase over ambient oxygen conditions.

° The concept of "Fire Propagation Index"

The "Fire Propagation Index" concept is set forth in the FMRC back-up document on their test method [67]. The derivation begins with standard textbook concepts of flame spread. However, the results are not expressed in terms of accepted engineering practice. For instance, in the use of HRR quantities, it is important that (1) the irradiance on the test specimen correctly represent the external heating expected during the fire scenario being considered, and (2) the bench-scale HRR results are meaningful only if the irradiance over the exposed face of the specimen is very nearly constant. The actual measurement conditions within the FMRC apparatus deviate radically from these requirements. In consequence, they obtain an equation for velocity of flame spread which may be dimensionally correct, but where the values of the various terms bear no relation to the theory itself.

The Fire Propagation Index is intended to represent the square root of the flame spread velocity. Although, this Index may correctly capture the essence of this velocity, such a velocity does not capture the essence of fire hazard. We discuss further (in the section on HRR) what is needed to obtain a true measure of fire hazard.

° Concerns with the assumed functional relationship for the TRP

"The procedure used by FMRC assumes a linear relationship to hold as long as the externally applied heat flux is sufficiently greater than the critical heat flux (below which there is no ignition or significant pyrolysis). The Thermal Response Parameter is determined only from this linear portion of the ignition time - heat flux relationship".

A recent Sandia Laboratories study [68] examines the FMRC procedure for deriving the TRP. In this study, Nicolette and Nowlen point out that data in the original FMRC studies leading to the method [69] show curves for piloted ignition and unpiloted to cross over. That result would imply that over a certain range of fluxes a specimen is easier to ignite if the pilot is removed, which is not correct.

A curious and controversial aspect of the development of this test method comes in a recent paper in which Tewarson and Zalosh [70] suggest that the ignitability and heat release rate data comprising the Fire Propagation Index can also be obtained from standard specimen tests conducted in HRR apparatus such as the Cone Calorimeter or the OSU apparatus. Tests run at ambient atmosphere on uniformly-heated specimens should give results different from those run at the conditions specified in the FMRC standard. If the results of one method could be derived from the other, then the more difficult and controversial test should not be needed.

Industry concerns with the FMRC standard

The usual procedure in developing a test method or standard is through consensus. This test method was developed without substantive changes based on input from industry or other concerned parties. As a result significant dissatisfaction has been voiced by industry representatives over various aspects of the FMRC rating scheme [63]. The concerns could be grouped into two areas: (a) the need for the test (i.e., the existence of other tests which provide better indication of performance); and (b) technical problems with the test (i.e., testing in enriched oxygen).

The issue of the necessity is quite crucial. While FMRC made presentations on the point that their cable-related losses have been increasing, there has been no breakdown of data given to indicate that the loss problem is associated with cables qualified under IEEE 383. It seems inappropriate to condemn the adequacy of IEEE 383 if data are not available to show that unacceptable losses are being sustained with cables that have successfully qualified under this test.

The most serious of the technical problems noted by industry [63] is that full scale validation efforts are incomplete because the performance of no Group 2 cables were ever verified in full-scale testing.

It was learned that certain statements on page 20 were being misinterpreted and the sequence of events related to UL 910 was inaccurately reported. Additional facts, not known to the authors at the time of publication, have also come to light. Accordingly, the twenty (20) lines following the first paragraph of §5, page 20 of the report should be replaced with the following:

It should be pointed out that the NEC provisions for testing of plenum cables did not come about because of any reported increase in plenum fires, since up to that point combustible materials were prohibited in plenums. Instead, it was desired to establish a test for unprotected wire and cable which would produce the same or less flame spread and smoke as wires and cables installed in metal conduit which was permitted at the time. This action was advocated by the Bell System who utilized high (fire) performance telephone cables and wished the additional flexibility of installing them in plenums without conduit.

A few years after the promulgation of UL 910 Kaufman and Yocum of Bell Laboratories published the results of a further study at UL in which an attempt was made to reproduce real plenum fires [45],[46]. They found that they had to use a very large ignition source (a 27 kg wood crib, producing approximately 350 kW at peak) to ignite and spread fire with various test cables. In their report they reported:

"...with the most severe [test] conditions, cables with both the original and improved materials performed well. Both had relatively low flame spread."

They go on:

"In comparison to the plenum, the tunnel test is more severe."

These tests showed the UL 910 exposure to be more severe than might be expected in practice at the time. In light of the increasing quantities of combustible materials found in some modern plenum spaces this conservative approach may be more appropriate.

Another issue related to UL 910 and the NEC surfaced in the 1987 code cycle with respect to jurisdiction over raised floors spaces in computer rooms which also served as plenums. NFPA 75 (Computer Facilities) imposed no special requirements on the cables, but if NFPA 90A (Air Conditioning Systems) were assigned jurisdiction, they would reference UL 910. Telephone cables already met UL 910 but the computer industry faced the potential of a substantial increase in required performance and costs. Jurisdiction of computer room sub floor spaces rests with NFPA 75 which defers to Article 645 of the NEC for wiring requirements within the space. Listed type DP cables will be required effective July 1, 1994 (in the 1993 NEC). Type DP cables are not required to meet UL910.

In addition, the first two sentences of the first paragraph on page 103 should be replaced with:

The UL 910 test presents some fundamental problems from the point of view of test design. The exposure has not been validated against typical plenum fire conditions. Given the current ability to perform fire hazard and fire risk assessments of products in their context of end use it is now possible for tests to measure *actual* performance and the conservatism to be accounted for through safety factors appropriate to the specific situation.

Corrections to NIST TN 1291

Please note the following additional editorial changes.

On page 16, Table 1; PLTC cable should be listed under UL 1581, not under UL 1666.

Ref. 133 is incomplete, it should read; Hasegawa, H.K., Staggs, K., and Fernandez-Pello, A.C., A Procedure for Ranking Fire Performance of Electrical Cables, Lawrence Livermore National Laboratory, Berkeley, CA 94550 USA.

On page 59, ref. 162 is incomplete, it should read; Gibbons, J.A.M., and Stevens, G.C., Limiting the Corrosion Hazard from Electrical Cables Involved in Fires, Fire Safety Journal, Vol. 15, No. 2, 183-190, 1989.

On page 59, second mention of ref. 162 is wrong; it should read ref. 202.

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Disclaimer

The findings and opinions expressed in this report are those of the National Institute of Standards and Technology (NIST) and do not necessarily represent the position of the National Electrical Manufacturers Association (NEMA) nor its member companies. Although the NEMA staff and a technical committee of the sponsoring companies had the opportunity to review and comment on a draft of this report prior to its release, in accordance with its normal policy these comments were considered advisory only, and were not binding on NIST.

Executive Summary

This report is the product of a thorough review of the literature on the fire performance of wire and cable products by the staff of the Building and Fire Research Laboratory (BFRL) of the National Institute of Standards and Technology (NIST). The purpose was to document the evolution of wire and cable testing as embodied in the myriad of standards and test methods presently in use for ostensibly evaluating those product's reaction to fire (which includes ignitability, burning rate, flame spread rate, and the rate of evolution of smoke and toxic or corrosive gases). As a result, 54 standard test methods from six countries are critically reviewed; including summaries of the testing procedures and comments on the historical basis, purpose, validation, and experience with each for which such was published. Where multiple tests are used to evaluate the same product (e.g., vertical tray cables), side-by-side comparisons of the various tests are provided. Where the current state-of-the-art in fire science reveals flaws in test design or instrumentation, such are detailed. While no attempt was made to cover every test method (particularly from the non-english literature), all major tests which have influenced or are influencing the development or philosophy of other tests in the international arena have been included.

In addition to standard test methods, important fire performance information on wire and cable products have been documented in experimental projects in both bench- and real-scale. Thus, the report presents a critical review of 47 bench-scale studies and 25 large-scale projects. In many cases, the results of these experiments reflect on the adequacy of the standard test methods, and these connections are made in the report. These range from strongly supportive (as for tests such as the UL 1666 riser cable tests, which present a realistic, real-scale fire scenario) to clearly negative (as for the FMRC test, where testing at 40% oxygen appears unjustified and where full scale validation efforts have been inadequate). In addition, systematic programs of testing have revealed factors which have important influences on the apparent performance of wire and cable (e.g., ignition source strength and location) and others with minimal impact (e.g., tray type). Such information can provide crucial guidance in evaluating the applicability of current tests and in the development of new tests. One observation regarding this staggering array of varying test methodologies is that it is *a direct result of the inability of current bench scale test methods to measure fundamental fire properties that can be used to predict fire performance under a variety of fire conditions.*

With the strengths and weaknesses of current methods for measuring the fire performance of wire and cable tabulated, the report describes the direction in which NIST, and most other fire science-oriented organizations in the world, are clearly headed — fire hazard and fire risk assessment methods supported by *measurement* methods based on heat release rate (HRR). With formal research programs to develop this technology in place in the US, Japan, Canada, Australia, and the European Community and NORDTEST (Nordic countries), the prevailing opinion is that nearly all of these test methods are obsolete and will be replaced by analytical methods which can predict the performance of products in their context of end use. The feasibility of this approach has been demonstrated with a range of products **including wire and cable**, although more development work is needed (particularly with respect to the prediction of flame spread) to address bundled cable applications adequately.

Five current models which have been applied to examining the fire performance of wire and cable are discussed along with some comments on needs for improvement. Several correlation methods which have been applied to predicting wire and cable fire performance are also presented as possible interim approaches until the needed model development and validation steps are completed.

The next section of the study presents a discussion of scenario based modeling of fire hazards as a proposal to begin to bring order from the chaos in which both the industry and regulators find themselves. With the assistance of the industry, a table identifying 25 generic types of wire and cable products and applications (with references to applicable NEC code provisions) was constructed (Table 3). For these products, fire performance concerns of regulators typically range from minimal (e.g., for direct burial cables or mineral insulated, metal clad cables) to significant (e.g., for building wire, tray cables, or plenum cables). By selecting the products which pose the highest level of *perceived* fire hazard and conducting a detailed fire hazard analysis, we would hope to quantify the *actual* fire hazard relative to other products found in the same environment. If the hazards of the wire and cable are small at the current level of product fire performance then no further regulation is necessary. Further, such a finding would confirm that *any product* with similar or lower heat release (and smoke/gas release) rates would result in the same or better fire performance in that application.

The report concludes with a summary of the important observations and findings, first regarding the test methods and experiments identified in the literature, and second with a summary of suggestions for a more rational approach for the future of wire and cable testing. These include specific comments on the test design and instrumentation, specification, and validation necessary for tests to be credible. Accordingly, a number of the major tests in use today need to be extensively modified or abandoned. The preferred approach of HRR-based testing supporting fire hazard and fire risk assessment methods is again cited along with suggestions for a continuation of the current effort to pursue this goal.

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Abstract

U.S. and Canadian reaction-to-fire tests for wire and cable are examined. The technical basis for their development is analyzed. The data requirements for engineering computations of fire hazard are examined. It is found that the current methods are primarily based on determining ignitability, speed of flame travel, or distance of flame propagation. The fire hazard to building occupants, however, is associated with the heat release rate of the fire, instead. Newer testing methods, which are not yet standards but which do measure the heat release rate of cables, are already under development. A limited comparison is made to British and international standards. Recommendations are made for improved testing strategies.

Key words: cables; flame spread; heat release rate; large scale fire tests; small scale fire tests; standards; test methods; wires

1 Introduction

Fire hazard analyses are gaining worldwide acceptance as means to establish the level of regulation needed to assure safe products without imposing unwarranted restrictions. In their efforts to harmonize regulations among the European nations, the EC Commission established the early goal that all fire tests selected should be consistent with fire hazard analysis procedures and provide the data needed by such techniques [1]. In Japan, the Building Research Institute of the Ministry of Construction (which promulgates the national building code and serve as the arbiter of its equivalency clauses) has formally established a fire hazard analysis procedure as one means of demonstrating the equivalency of new products and materials to their code requirements [2]. Australia is developing a similar system through its Warren Centre for Advanced Engineering (Univ. of Sydney) and CSIRO Division of Building, Construction and Engineering [3]. Sweden, Norway, Denmark, Germany, France, and Singapore all have established the precedent of accepting new products, materials, or designs based on fire hazard or fire risk analysis calculations.

In the United States, in 1985 a National Electrical Code panel concluded that additional regulation of certain plenum cables was not warranted, based on a fire hazard analysis calculation [4]. While unfortunately this single case has not been followed by other examples of the application of fire hazard analysis to wire and cable regulation, most authorities state that such would be seriously considered on a case by case basis.

In support of demonstrating the viability of fire hazard analyses of wire and cable in the context of their end use, that industry, through the National Electrical Manufacturers Association (NEMA), funded a research project at the Building and Fire Research Laboratory (BFRL) at the National Institute of Standards and Technology (NIST). The first phase of this work was to evaluate the state-of-the-art of fire testing of wire and cable products with a view toward the degree to which such testing supports the conduct of fire hazard analysis. The design of these test methods would also be reviewed in light of modern techniques of good technical practice and their ability to address properly the product fire performance. Finally, this phase would review the literature on small- and real-scale fire testing of wire and cable and identify those tests which could be used to support and validate fire hazard analyses of these products.

Following this initial effort, a second phase study was envisioned in which fire hazard analyses would be performed for a range of wire and cable products and applications regulated by the codes. This analysis, supported by the testing identified in the literature and any other testing deemed necessary, would demonstrate the ability of these techniques to address the fire performance of these products properly. Further, the range of cases studied will identify the importance of these products relative to other combustible items normally found in the end application. In this way it is hoped that the areas where regulation might provide more safety for the same expenditure might be identified.

1.1 The Dual Nature of Wire and Cable

Traditionally, wire and cable have been regulated as part of the building structure, largely since most of

it was installed during construction and was available for inspection with the plumbing, mechanical, and other building systems. This is often no longer the case. In many modern buildings, particularly office and mercantile uses, the explosion in information systems (computers and point-of-sale terminals) has resulted in large quantities of wire and cable being pulled in existing structures. While often located in the same spaces (within walls and above ceilings) as cable installed during construction, this product is considered *contents* and is largely unregulated, other than those classed as plenum cables.

The traditional approach to regulation, that is the pass/fail test methods, still dominate the structural fire resistance/flammability applications. The tendency among those examining the regulation of contents again is to apply fire hazard analyses, if not directly, then at least to establish the safe limits of performance. This is evident with current activities in the regulation of upholstered furniture and with mattresses [5]. Properly executed, there is no reason why the fire hazard approach could not also be employed to understand the performance of wire and cable whenever or however such products are used.

1.2 Scope

In this study bench-, medium-, and large-scale cable test methods which are in wide use in the United States and in Canada are reviewed. Tests conducted in actual end-use configurations (termed here “real-scale tests,”) will be reviewed. For comparison, some standards from Great Britain and several other European countries will also be examined. The standards chosen for this examination are ones of historical interest, primarily those which were influential in the development of the current generation of international standards issued by IEC (International Electrotechnical Commission). Finally, the IEC standards themselves will be examined and, to the extent possible, compared with U.S. standards. In addition to test standards, some original work on assessing cable flammability by means of nonstandard procedures as well as newer procedures and studies which, while not yet having achieved the status of standards, provide valuable data for the needs of the fire protection engineer. Significant studies of this nature are also reviewed.

In the United States, certain general cable flammability requirements are set down in the National Electrical Code [6] (NEC). Specific testing requirements are then defined by testing laboratory (e.g., Underwriters Laboratories, Canadian Standards Association, etc.) standards. These requirements will be considered in some detail. Additional requirements are laid down in the purchase specifications of various organizations. These include the Department of Defense, the U.S. Nuclear Regulatory Commission, various transportation authorities, and other large organizations. Some of the highlights of such procurement specifications will be reviewed, but it is not possible, obviously, to survey such specifications in totality.

The primary focus will be on the traditional two aspects of testing: flammability and smoke. Concerns are also common in recent years about corrosivity and toxicity aspects of fire performance. It will be readily obvious to the reader, however, that while there has been a certain general agreement on testing philosophy for, say, vertical cable tray fire tests, there has been very little agreement about corrosivity or toxicity requirements. Nonetheless, some of the more pertinent of those will be reviewed.

1.3 Literature Surveys

Preliminary to starting work on this project, we examined prior surveys of the literature of wire and cable flammability. Hilado and Huttlinger conducted such a survey in 1981 [7]. They, however, found only a total of 47 references. In the United Kingdom, the Electrical Research Association conducted a literature study on this topic in 1972 [8]. This predates most of the current methods and, thus, would be interesting only for historical purposes. A general state-of-the-art survey on cable flammability was published by the National Materials Advisory Board in 1978 [9]; the discussion of testing issues in this study, however, is minimal.

Our own search strategy included the FIREDOC database maintained at NIST, plus the databases of the Rubber and Plastics Research Association, the Engineering Index, and the National Technical Information Service. In FIREDOC we found over 1000 references to wire and cable topics. About 10% were 'false hits,' *e.g.*, wire rope, wire glass windows, etc. The remaining studies generally fell into two categories: (1) descriptions of new products or materials, and (2) test method development studies or experimental fires. The former was not within the scope of the study; the latter were the items examined in detail.

In addition, we have interpreted many of the assumptions and procedures used in the electric wire and cable testing field in the light of general principles of fire protection engineering; this portion of the study, however, was not accompanied by a separate literature search.

1.4 The Scale of Tests and the Need for Validation

Fire tests on materials and products are normally divided into two categories: Fire endurance and Reaction to fire. The former category is concerned with the performance of a product as a barrier to fire propagation or as a load-bearing member. This will, with a few very specialized exceptions, not be of significant interest in the wire and cable area. Reaction-to-fire tests, on the other hand, comprise aspects such as ignitability, flame spread, heat release rate, and the production of visible smoke, corrosive products, or toxic products of combustion.

In the analysis of existing and proposed test methods, it is important to consider carefully the scale of the test. Tests can be grouped into three types:

- Bench-scale tests
- Real-scale tests
- Tests falling in between these two types. These have been called intermediate-scale, mock-up scale, large-scale, and similar terms.

A real-scale test, by definition, re-creates all the essential features of an actual fire. Thus, its results do not need to be validated against a larger-yet benchmark. There are, however, two requirements for data from a real-scale test to be valid:

- (1) The fire scenario chosen must realistically create the fire situation of concern.
- (2) The measuring instruments and data analysis must be consistent with sound, current engineering practice.

For any other tests, validation is necessary. A bench-scale test has no validity in and of itself. Its only utility comes when its results have been used to predict successfully real-scale results. Bench-scale tests (also referred to as small-scale tests) are so called because the apparatus is of a size that it can be housed on a laboratory bench.

In between the bench-scale and the real-scale, there are a number of possible test arrangements where the scale is moderately large, yet the complete actual fire environment is not being created. An example of such a test is the furniture calorimeter test [10]. In that test, the scale of the article under test is exactly the same as in real life. The environment, however, is different—the test article is burned away from any walls and with a functionally unlimited supply of air. As a result, a furniture calorimeter test can represent only certain variables of the real-scale fire (*e.g.*, heat release rate, but not CO production) and only with certain limitations of maximum heat release rate. Thus, encountering these less-than-real-scale fire tests, one must examine them for validity. Such an intermediate-scale test may make easy the portrayal of certain features which are not represented in a bench-scale test (for instance, geometry effects), but its results still lack credibility until validated.

2 Early Test Methods

Ever since the electric power industry came to exist there has been concern about wiring overheating due to excessive current being drawn through a particular wire. This concern was addressed by establishing ampacity tables, where the property of the insulation being examined is its heat rating. This is not a fire test, *per se*. When increasing current is being drawn through a wire, the danger point is reached when degradation—not flaming—of the insulation material first occurs. Thus, with regards to overheating due to excessive current being drawn, the test procedures are not fire tests, and we do not consider them further in this study. The concern over the flammability of electric wire and cable is relatively recent.

An electric cable fire may start due to either an electric fault or due to an external ignition source. Circuit protection devices, when properly used, minimize but do not eliminate the possibility of arcing and ignition possible under conditions of abrupt, extreme overload. The general experience, however, is that it is much more likely that a cable fire will occur when an external ignition source and fuel load are present (stored rubbish, etc.) than when no supplementary fuel is available. A pair of companion studies by the NFPA in 1966 [11],[12] amply demonstrated this fact. In these studies, a large number of cable-fire incidents were examined. In almost all cases, it was concluded that the single most important factor was an external ignition source and an exacerbating factor in establishing the seriousness of the fire loss was the presence of nearby supplementary fuel.

Thus, it becomes appropriate to consider the nonmetallic portions of cables as **fuel load**, but not to consider an electric fault as the **ignition source**, since substantially more hazardous ones can be found from nearby combustibles. Thus, modern-day fire tests for electric cables typically consider **exposure** fires, that is, the wire/cable is not the first to ignite, but ignites from another, already burning object. Electric-fault ignition testing is seen to be largely unnecessary, in consequence, since it is more difficult for a specimen to pass a reasonable test against external-source ignition than against an electric-fault ignition test. Some systematic test evidence for this has come from a recent test program at Sandia Laboratories [13].

During the 1960's and 1970's, two significant changes in construction and wiring practices occurred: (1) the increasing use of non-metallic sheathed cable, replacing the earlier metallic sheathed cable, and (2) the increasing use of cable trays, wherein cables without metallic sheathing would be placed. The latter was of most concern in nuclear power plants, but was of issue in various other industrial occupancies.

During the 1980's the concerns became more severe, due to significant changes in communications cabling. Prior to the 1980's communications cabling was primarily of a single type: telephone wiring, installed by the Bell System companies. The telephone companies used their own Bell System Technical Practices for specification purposes and fire and functionality issues were, effectively, self-policed. Also, prior to the 1980's very little of other communications wiring was common. Computer room facilities were generally localized and specialized and there was not a concern over computer cabling.

2.1 Small Burner Tests

To understand the thrust of fire testing concerns, we have to consider appliances, as opposed to buildings. Electric appliances can contain motors, heaters, transformers, and other components which can overheat or possibly ignite. Within an appliance, however, the wiring is usually not run in metallic sheathing, but is rather exposed to the interior of the device. Thus, there is potential for ignition or rapid burning. A research study on the general question of flammability of plastics used inside appliances was conducted by Underwriters Laboratories (UL) in 1964 [14].

As examples of the early ‘flame’ tests for wires is ASTM D 470 for braided wire insulations and jackets [15]. This test specifies a Tirrill burner fed with illuminating (!) gas.¹ A 254 mm long horizontal test specimen is used in this test; observation is for extent of flames and for any ignition of surgical cotton placed below the specimen.

One slight step up in severity is the vertical burner test described in ASTM D 2633 [16]. This test was developed in the 1960’s and, consequently specifies natural gas, rather than illuminating gas, for the Tirrill burner. A 560 mm long specimen is used, stretched taut vertically. The gas burner is inclined 20° from vertical. Slightly different criteria are used, which include placing a paper tab on the specimen, which must not be more than 25% burned during test. UL Standard 44 (Rubber-Insulated Wires and Cables), UL Standard 62 (Flexible Cord and Fixture Wire) and UL Standard 83 (Thermoplastic-Insulated Wires) specify similar procedures except that the specimen length is only 457 mm. Some additional information on the historical development of the UL tests for wire flammability is given by Gaffney [17], who discusses in detail the ‘FR-1’ version of the vertical small burner test that is used in the UL standards, now known as the VW-1 test.

There has been a vast number of other, similar tests developed where a single wire is exposed to a small burner flame. We will not review all of these here, since the principles are largely redundant to the ones already mentioned. There appears to be general consensus within the profession that such tests do an adequate job of providing a baseline safety level for wiring within appliances, in residential uses, in low power applications, and similar situations. However, very little of this information is useful in a general hazard analysis.

¹ It should be noted here that in current-day America electricity, rather than gas, is normally used for illumination. This situation notwithstanding, this standard is still on the books of ASTM.

3 U.S. Test Methods

3.1 Cable Tests—the IEEE 383 Test

The above small burner type tests were intended for testing a single wire. During the late 1960's and the early 1970's, some concern arose with cables which might be used on open cable trays or ladders and lack any metallic sheathing. Thus, during the 1960's a significant effort was launched by a number of utilities and related companies to develop a realistic test. Such tests were proposed by:

- Philadelphia Electric Co.
- Baltimore Gas and Electric Co.
- Consolidated Edison Co.
- Detroit Edison Co.
- Raychem Co.

and others. McIlveen [18] and DeLucia [19] reviewed some of these efforts. Of most direct relevance was a vertical tray test developed by the Philadelphia Electric Co. After a 1965 fire in Unit 1 in their Peach Bottom Atomic Station, an effort was made to develop a suitable cable tray test. Details of the development effort are not available, but a summary is contained in an article by Forencsik [20] and in a review by EPRI [21]. The Philadelphia test was incorporated into their Specification D-225924 and used an 0.15 m wide tray, 4 m high. Cable loadings were specified to be 7C/#12 AWG or 7C/#14 AWG. Ignition was a burlap bag, soaked in transformer oil and stuffed into a wire basket. The test criteria included both flame travel and circuit continuity. The tests proposed by Consolidated Edison and Baltimore Gas and Electric used a burning pan of oil instead of oil-soaked rags.

Further development of a test for tray cables was done at General Electric Co. [22] and at Okonite [23]. The above tests were somewhat realistic in that they used substantial size oil pans, burning rags, and similar ignition sources. As might be expected with crude simulations, however, repeatability and reproducibility problems were foreseen, and none of these tests were proposed as standards.

In terms of standardization beyond a single company, the first larger-specimen test suggested for use as a standard method was proposed by IEEE's Working Group on Wire and Cable Systems in 1971 [24]. The method used a cable which is 3 ft long. Ignition was from a Fisher² burner. Two different tests were proposed. In the horizontal test, the cable was installed in a horizontal cable tray; in the vertical test the cable tray was vertical, while the burner was inclined at 30°. Unlike 'screwdriver' type tests,³ the

² 'Fisher burner' is not an accepted technical designation; we surmise the standard may be referring to a Meker burner manufactured by the Fisher Scientific company.

³ There are a number of old reaction-to-fire tests where a screwdriver is the primary measuring tool. The screwdriver is used to scrape the soot from the burned specimen after test, then to scratch further to determine the boundary between the damaged region and the undamaged. Such

main criterion used here was electric circuit integrity, not extent of surface damage. The published draft also contained a number of discussion comments from various persons. Relevant comments included observations that:

- The flame source used was too small; a flame to engulf the end of the tray and provide a uniform heating condition was needed, instead.
- The suggested tray length of 0.6 m was too short and 0.9 or 1.2 m would be better for observing flame spread.
- Monitoring of circuit integrity was extremely irreproducible, depending primarily on the vagaries of how the cables bend and fall during test (which determines when and if bare sections touch).

IEEE did not adopt this suggestion but, rather, accepted a modified version of the method as proposed by Okonite. The original Okonite studies involved a circular burner and a combined horizontal/vertical tray arrangement. The tray arrangement was soon simplified to vertical-only, since that was the more challenging orientation. The burner was also changed during development, with the IEEE standard [25] prescribing a ribbon burner, not a circular burner. Perhaps the most important change was the dropping of the circuit continuity test requirement. This allowed thermoplastic materials to pass, which would have failed the continuity requirements [21]. The reasons why the circuit continuity requirement was dropped has to do with regulations requiring redundancy in certain nuclear power plant functions; this topic is outside of the scope of the present study. Curiously, an 'alternative' ignition source, comprising the oily rag test developed by Philadelphia Electric Co., was also included as a permissible test option.

To summarize, the features of the IEEE 383 standard, as adopted in 1974, are:

- A vertical metal tray, 0.31 m wide and 2.4 m high;
- A single layer of cable specimens, to be arranged to fill at least the central 0.15 m width of the tray, with a separation of approximately 1/2 the cable diameter between each cable;
- A specified, ribbon-type of gas burner is located with its face 75 mm *behind* and 0.6 m above the bottom of the cable tray;

methods have been common not only in the wire and cable field. They have two serious drawbacks, however: (1) Because visual observation, rather than a measuring instrument, is used, repeatability and reproducibility are very difficult to achieve. (2) The variable measured is not an engineering property which can be used for quantitative assessment of fire hazard. We will examine later in this study newer test methods which do not suffer from these drawbacks.

- The burner is supplied by a propane/compressed air mixture. The actual rate of 21 kW⁴ is not mentioned in the standard; instead, air and gas pressures to be monitored at certain places in the gas train are specified, as is a flame temperature of 816 °C, to be measured at 3 mm from the specimen;
- The burner flame is applied to the specimen for 1200 s;
- Three test runs are required;
- The specimen passes if the burn damage is less than the total 2.4 m specimen length.

In addition to the propane burner, details are also given on the alternative, oil-soaked burlap rag ignition source.

3.1.1 Studies on Improvements to the IEEE 383

UL studies

During 1974-76 the Nuclear Energy Liability-Property Insurance Association (now the American Nuclear Insurers) sponsored a test program [26] at UL to obtain information on the importance of certain test parameters. The variables to be examined were:

- Burner output level—values of 62 kW and 134 kW were to be compared to the standard 21 kW level;
- Performance of cables in the horizontal orientation was to be compared against those in the vertical;
- Results from circuit integrity tests, even though those were not adopted by IEEE;
- Examine the effect of placing the cable tray close to a wall corner, rather than being far away from walls. This was presumed to increase test severity by re-radiating heat to the specimen.

In the vertical tray test, when different burner outputs were used, the distance between the burner and the cable tray had to be adjusted to make sure that the flames still wrapped up against the cables, instead of merely shooting out past them. This dimension is 75 mm for the 21 kW test, and was set at 127 mm for the 62 kW tests and at 280 mm for the 134 kW tests.

⁴ The industry has been using burner outputs based on the gross heat of combustion of propane. For the sake of clarity, we will also refer to burner outputs this way in the present review. Such a practice, however, is not appropriate for the combustion systems involved. The phase change of H₂O (g) → H₂O (ℓ) does not occur, therefore, it is incorrect to use the gross heat of combustion. The net heat of combustion for propane is 46.36 MJ/kg, compared to 50.35 MJ/kg for the gross heat of combustion.

In the horizontal tray tests, a geometry was created whereby four horizontal trays were placed one above the other, spaced 30 cm apart. This quite closely simulated a possible actual-use situation and comprised a more severe test condition than simply testing a single tray alone. The same three burner levels were used for the horizontal tests as for the vertical ones. The horizontal tests were carried out in two room arrangements, one where only one wall was close to the specimens, and a second where the room size was made smaller and the ventilation decreased so as to check whether room heating seriously effects cable performance.

The reduced room size/reduced ventilation horizontal test condition resulted in 20% - 30% greater cable damage than the larger room test condition.

The test results showed that:

- As the ignition source intensity was increased greater performance differences between cable types were found;
- There were some rank-order reversals as the ignition size was increased;
- The initial period of burner flame application sometimes resulted in swelling of cables, with the flames subsequently not being able to penetrate through the spaces to the far side of the specimens. This effect was troublesome at the 21 kW level, but not with the larger ignition sources;
- Repeatability was better at the higher ignition source intensities;
- The horizontal orientation tests proved to be a less severe test condition, even though multiple stacked (vertically) trays were used;
- There was no general relationship between extent of char damage and circuit integrity;
- Circuit integrity results were rank-ordered similarly regardless of which burner level or specimen orientation was used.

It appears that no answer was obtained to the question of what the effect was of placing the cable tray close to a wall corner, rather than being far away from the walls.

The UL studies were continued in a Phase II investigation during 1976-78 [27]. The variables to be investigated in this series were:

- The effect of changing from a single burner to two burners;
- Packing density effects;
- Effects of ambient temperature and ventilation;
- Further studies on ignition source intensity and specimen orientation.

The major results were:

- In the horizontal orientation, a considerable effect of ventilation was found on the test results. Flame propagation was generally higher with more abundant ventilation, but the effect was not otherwise quantified;
- In the vertical orientation, the worst-case packing density depended upon the ignition source strength. A lower fraction of the cable tray (20%) needed to be filled at the 21 kW level than with the larger ignition sources (30%);
- In contrast to the vertical orientation situation, in the horizontal orientation it was found that increased loading of the cable tray invariably resulted in higher flame propagation.

Data analysis comparing the two-burner results to single-burner results was not carried out.

The last series of studies on this topic was carried out at UL during 1978-1980 for the Nuclear Regulatory Commission, which wanted to determine if improvements to the IEEE 383 were needed. A large number of experiments were conducted by UL, with the following being the essential conclusions [28],[29],[30]:

- The standard does not prescribe how, or at what intervals, the cables should be tied down to the tray. Some cable types are sensitive to the tie-down interval, showing much greater flame travel if not secured at frequent intervals. The standard should specify the use of steel tie wire, not allowing plastic cable ties, which break loose early during test;
- A lower temperature of the test room can cause shorter flame travel;
- The type of cable tray used can influence the test results and should be specified in detail;
- The only practical way to guard against 'spurious air currents' is to provide an enclosing cabinet. Both the dimensions and the ventilation rate should be specified. A ventilation rate of $708 \text{ L}\cdot\text{s}^{-1}$ was suggested;
- The method mandated in the standard for controlling the flow rates of gas and air (by monitoring line pressure) is inadequate and irreproducible. Rotameters should be specified and gas densities should be taken into account. The monitoring of flame temperature should be dropped, since it does not provide a good indication of correct flows.

A few years later, UL was again asked by NRC to conduct another detailed study on the same topic [31]. The recommendations were nearly similar as previously, with an important addition:

- Instrumentation for making heat release rate (HRR) measurements should be added.

ICEA studies

In 1984 the Insulated Cable Engineers Association conducted a round robin on the IEEE 383 tests [32]. As part of the round robin, a number of vague or unspecified aspects of the IEEE 383 were examined, with an eye towards tighter standardization. In the ICEA round-robin program three different

series of experiments were run, with a progressive tightening up of instructions. The first series was run, essentially, without supplementing the standard by additional instructions. The coefficient of variation obtained for the burnt-length measurement was 24.6%. In the second series, additional instructions were given on the number of specimens to test, the spacing to maintain, and instructions on how to tie the specimen to the cable tray. The coefficient of variation obtained was 32.3%. In the third series, a minimum specimen initial temperature was specified, as were additional instructions on how to control the burner output and how to position the burner. A thicker gauge for the tie wires was also called for. For the third series, an average coefficient of variation of 18.0% was achieved, averaged over tests of four different types of specimen.

The main conclusions of the study were:

- The test “does not provide for control of test procedures or environmental conditions to the extent necessary to produce satisfactorily consistent results among different laboratories”;
- The test procedure should more specifically address control of combustion gas and air, number of specimens, specimen spacing and method of position fixing, burner location, burner type, environmental condition limits and specimen temperature;
- While having a test enclosure was deemed essential, neither the exact size of enclosure used nor the air flow through it were found to be important.

The conclusions all seem to be supported by the data, with a few exceptions. The conclusion that the burner *type* be better standardized seems to be a miscommunication. The burner is specified by an exact catalogue number in IEEE 383 and was unchanged for this program. It is likely that what was meant is that type of fuel and air control to the burner must be better specified. With regard to environmental conditions and specimen temperature, these were not explored in the ICEA test program as variables the effects of which could be isolated. Thus, we refer to later studies on this issue, examined elsewhere in this review, where a different point of view is expressed.

For a long time, no action was taken with regard to the recommendations of either UL or the ICEA, and the 1974 edition of IEEE 383 continued (and indeed, continues—until specifications using it are changed) to be in effect. However, a Working Group of the Power Equipment Subcommittee of the Power Systems Engineering Committee of the IEEE Industrial Applications Society was eventually charged with developing a replacement. The replacement standard has a new number, IEEE 1202, and is discussed later. The method follows closely CSA FT-4 (see below), rather than the existing IEEE 383-1974. Since the new standard was released just before completion of this review, there is not much experience with it, nor do regulatory bodies yet refer to it. Thus, we will be devoting much more attention to IEEE 383 than IEEE 1202 in this review.

The IEEE 383 test is an intermediate-scale test. As a result, validation results against real-scale fires should be demanded. While some anecdotal references to the performance of this test in predicting real-scale fires may be available, we find no record of a systematic validation effort. As a minimum, we see such a validation as requisite. As is discussed in later section, however, a better strategy may to be espouse the use of bench-scale HRR testing, in preference to this intermediate-scale test.

3.2 The National Electrical Code Requirements

In the United States, the primary requirements for electric wire and cable performance are those laid down by The National Electrical Code (NEC) [33]. The Code does not provide for any 'general' requirements. Instead, different requirements are prescribed for different types of wire and cable. The provisions in the NEC have been changing substantially in each revision of the Code. Here we examine the provisions of the current (1990) edition. The requirements of the NEC for reaction-to-fire testing of wire and cable are summarized in Table 1. A brief description of the categories of wire and cable for which requirements are laid down are listed below. We will review in detail the tests that are mandated for testing each category.

Communications cables are divided by the NEC into the following types (Article 800):

CMP	used in plenums
CMR	used in vertical riser shafts
CM	general purpose, except in plenums and vertical riser shafts
CMX	limited use; for dwellings and for use in raceways
CMUC	for use under carpets

MPP, MPR, MP these are multi-purpose cables which meet both the requirements of the pertinent communications cable type and also certain requirements pertinent to fire protection signalling cables

Optical fiber cables generally follow the same classification as for metallic communications cables (Article 770):

OFCP, OFNP	used in plenums
OFCR, OFNR	used in vertical riser shafts
OFC, OFN	general purpose, except in plenums and vertical shafts

Fire protection signalling cables are also classified in a similar manner (Article 760):

FPLP	used in plenums
FPLR	used in vertical riser shafts
FPL	general purpose, except in plenums and vertical shafts

Remote-control, signalling, and power-limited circuit cables (Article 725):

CL2P, CL3P	used in plenums
CL2R, CL3R	used in vertical riser shafts
CL2, CL3	general purpose, except in plenums and vertical shafts
CL2X, CL3X	limited use
PLTC	power-limited tray cable, for use in hazardous locations

Table 1. Summary of UL tests identified according to NEC cable types

Test method	NEC cable type	Heat output from burner ^a (kW)	Smoke measurements
UL 1581 Vertical wire flame test (VW-1)	CMX, CMUC, CL2X, CL3X, CATVX	0.88	no
UL 854 Service entrance cable vertical flame test	SER, SEU	0.88	no
UL 1581 Vertical tray flame test /IEEE 383	CM, MP, OFC, OFN, CL2, CL3, CATV tray use: MCMV, THHN, THWN, THW, TC, RHH, RHW, XHHW	20.5	no
Proposed UL 1685 for Optional LS rating (some cable types listed may not pass in smaller sizes)	AC, DP, E, MC, MTW, MV, NM, NMC, RFHH, RHH, RHW, SIS, SNM, TC, TF, TFF, TFN, TFFN, THHN, THW, THWN, TW, XF, XFF, XHHW, ZW	20.5	Pk SRR $\leq 0.25 \text{ m}^2 \cdot \text{s}^{-1}$ Total smoke $\leq 95 \text{ m}^2$
UL 1666 Riser test	CMR, MPR, OFCR, OFNR, CL2R, CL3R, PLTC, CATVR	154	no
UL 910/NFPA 262	CMP, MPP, OFCP, OFNP, CL2P, CL3P, CATVP	88	yes
a. The tests are ranked in terms of generally-reported severity, based on test results. This corresponds to the heat output from the burner in some, but not all, cases.			

Community antenna television cables (Article 820):

CATVP	used in plenums
CATVR	used in vertical riser shafts
CATV	general purpose, except in plenums and vertical shafts
CATVX	limited use

The UL 1581/Vertical wire flame test (VW-1)

UL standard 1581 [34] has a number of test procedures defined within it. The VW-1 vertical wire flame test is a Tirrill burner test similar to ASTM D2633 and related tests discussed above. In this test the burner flame is applied five times for 15 s each time. The time between applications of flame is 15 s, providing the specimens stops flaming by the end of this 'off' period. If the specimen does not stop flaming, then the re-application is delayed until it does.

The UL 854/Service entrance cable vertical flame test

UL standard 854 [35] prescribes a test procedure used for testing service entrance cable types SER and SEU as defined in the NEC. The same vertical flame test is also used for testing appliance wiring which is intended for use external to the equipment (UL Subject 758 - proposed). It is also currently used for computer room under-floor cable testing; however, the 1993 NEC requirements are proposed to be changed to require the UL 1581 vertical tray flame test instead for this application. The test method uses the same apparatus as the VW-1 test and differs only in the length of time that the burner flame is applied (3 times each, 60 s on, then 30 s off).

The UL 1581/Vertical tray flame test

This test is required for all wires and cables to be used in cable trays and is essentially identical to the IEEE 383 test already discussed. The differences are primarily that certain procedures are more fully spelled out, and are:

- The size of the channel rungs on the cable tray is specified, as is their spacing.
- The centerpoint of the face of the burner is specified to be 0.45 m above the bottom of the tray, instead of 0.6 m.
- Actual volumetric gas and air flow rates required are specified, not just the pressures to be monitored at gas train pressure gauges. No mention is made of monitoring a flame temperature.
- A more detailed instruction of how to conduct a 'screwdriver' determination of damage is given.
- A requirement is not made for testing three specimens.
- No provision for testing with an oily burlap cloth is made.

Additional features of this test are shown in Table 2.

Table 2. Summary comparison of some features of vertical cable tray tests

	IEEE 383 UL 1581	ICEA T-29-520	CSA FT-4	IEEE 1202	UL 1685 /UL ^a	UL 1685 /IEEE ^b	IEC 332-3
Burner power (kW)	21	62	20	20	21	21	20
Time of flame (min)	20	20	20	20	20	20	20, 40 ^g
Alternate source	Yes, oily rag ^d	no	no	no	no	no	no
Burner placement ^c	600 mm ^e 75 mm in back	300mm 200 mm in back	300 mm 75 mm in front	300 mm 75 mm in front	457 mm 75mm in back	457 mm 75 mm in front	600 mm 75 mm in front
Angle of burner	horiz.	horiz.	20° up	20° up	horiz.	20° up	horiz.
Tray length (m)	2.4	2.4	3.0	2.4	2.4	2.4	3.5
Tray width (m)	0.3	0.3	0.3	0.3	0.3	0.3	0.5
Sample length (m)	2.4	2.4	2.3	2.3	2.4	2.4	3.5 m
Width of tray used for cables (m)	0.15 front only	0.15	0.25 front only	full front only	0.15 front only	full front only	0.30 front or front + back ⁱ
Thin-size cables to be bundled	no	no	if D < 13 mm	if D < 13 mm	no	if D < 13 mm	mounted flush, with no spaces
Test enclosure specified	no	no	yes	yes	yes	yes	yes
Required air flow rate	N.A.	N.A.	> 0.17 m ³ /s	0.65 m ³ /s	5 m ³ /s	5 m ³ /s	^h
Test runs needed	3	2	2	2 x 2 ^f	1	1	1
Max. char length (m, from bottom)	2.4	2.4	1.786	1.786	2.4	1.786	3.1
Peak smoke release rate (m ² s ⁻¹)	N.A.	N.A.	N.A.	N.A.	0.25	0.40	N.A.
Tot. smoke released (m ²)	N.A.	N.A.	N.A.	N.A.	95	150	N.A.
^a (proposed) Version run with UL 1581 exposure. ^b Version with CSA FT-4/IEEE 1202 exposure. ^c Height above bottom, distance from specimen surface. ^d Not applicable in the UL 1581 version. ^e This dimension is 457 mm in the UL 1581 version. ^f Two each on two different sizes of specimens. ^g Time is 20 min for Category C, 40 min for Categories A and B. ^h Not yet specified. ⁱ Depends on amount of cable loading.							

The UL 910 test for plenum cables

In 1975 the NEC adopted provisions requiring that cables used in plenums have “inherent fire-resistant and low smoke producing characteristics.” The 1975 Code did not prescribe how the testing should be done, but UL responded by developing a test that came to be known as the UL 910 [36]. Their development program set for itself as objectives [37]:

- A high heat flux characteristic of actual fires (60-70 kW/m²) is needed;
- Large flame coverage of the test samples is needed in order to provide a high heat input to the cables;
- The test sample should be mounted horizontally in order to simulate actual conditions in a plenum;
- Multiple cable samples of sufficient length should be tested in order to simulate actual installation and to provide a realistic amount of combustibles;
- The test facility should be insulated in order to provide conservation of heat energy;
- A movement of air over the test samples is needed to provide oxygen for combustion and to promote flame propagation;
- The test must be of sufficient duration to allow the flame spread to achieve a peak value.

Historically, this is simply a description of the conditions which appertain in the Steiner Tunnel test [38]. It is, therefore, not surprising that the NEC adopted the Steiner Tunnel test as the tool for development of the standard.

The resulting UL 910 test for plenum cables was basically the Steiner Tunnel with some modifications. The main modifications were increasing test time from 10 to 20 min, and also establishing flame spread and smoke classifications which were specified to cables. The work was not accompanied by any full-scale testing nor discussion of actual fires. Instead, several of the objectives quoted above contained reference to an earlier UL study on *room* fires [39].

In 1971, Forensik stated that with regards to cable tray fires, “adequate ventilation is very important because of the dense smoke generated by most burning cable insulations” [20]. This was not incorporated into the IEEE 383. Instead, the first time a smoke provision appears in the NEC is in connection with the testing of plenum cables in the 1975 NEC.

Several important observations can now be made in regard to the development of this standard:

- (1) A plenum fire is *not* a room fire. A room fire, if serious, is characterized by a large, readily combustible fuel load. The Steiner Tunnel simulated a very serious external ignition source impinging upon the specimen. Such an ignition source is improbable, if not impossible, in a plenum.

A room fire also has a large ventilation available from broken windows or failed doors. A plenum, however, typically contains only negligible amounts of air. Although used as a return air duct, the ventilation rate is still considerably below that in an open space typified by a room;

(2) In 1975 there was a serious disillusionment with bench-scale fire tests, due to the action by the Federal Trade Commission against misleading fire tests [40]. In the intervening years, a number of appropriate, high-quality bench-scale fire tests have been developed. The profession has realized that, in most cases, use of bench-scale, rather than large-scale tests is preferable. The reasons have to do with cost, reproducibility, and utility of data. On the latter point, it turns out that data from bench-scale tests are often much more suitable for fire engineering calculations than are the results of a single-scenario larger-scale test. Reference [41] contains further details on this topic;

(3) Heat release rate (HRR), rather than flame travel, is now seen as the key to fire safety design [42]. Flame extent distances, needed in some engineering computations, are often readily available as a by-product of bench-scale HRR testing. The connection between HRR tests and performance will be discussed in chapter 8;

(4) While smoke measurements are made in UL 910, their results are arbitrary. The smoke readings obtained in the Steiner Tunnel do not reflect a measurable 'property' of the test specimen, and cannot be used in engineering computations to predict smoke hazard in actual fire conditions (details of smoke measuring techniques which are acceptable for engineering computations are given in Ref. [43]).

(5) In order to avoid the controversy cited in (2), bench-scale tests must be validated against real-scale fires. A connection must be made between the results obtained from the bench-scale tests and the behavior that is being analyzed. In this sense, real-scale tests do not need a 'scale' validation. There does need, however, to be a demonstration that the physical fire scenario created corresponds to actual, known fire hazards. The development of the UL 910 was accompanied by more illustrative test data in a second publication [44], but not by an examination of actual-fire hazard conditions.

At this point, it must be pointed out that the NEC provision did not come about because of any reported increase in plenum fires. Instead, there was a competitive positioning between the Bell System on the one side and computer manufacturers on the other. The Bell System had restrictive in-house standards and, consequently, were manufacturing plenum cable to a high degree of fire performance. Computer manufacturers were generally producing cables only to meet the requirements imposed by fires that had actually occurred and had not been marketing such high-performance products (normally highly-fluorinated polymers are needed to pass UL 910). The introduction of UL 910 test insured that the design imposed by Bell would be required. Very interestingly, a few years later Kaufman and Yocum, of Bell Laboratories published the results of a further study conducted at UL in which an attempt was made to create real plenum fires [45],[46]. They found that they had to use an exceedingly large ignition source (a 27 kg wood crib, producing approximately 350 kW) to ignite and spread fire with various test cables. Much to their credit, Kaufman and Yocum did publish the results of their study and reported that:

"...with the most severe [test] conditions, cables with both the original and improved materials performed well. Both had relatively low flame spread."

In other words, even with an overwhelmingly large ignition source it proved impossible under conditions which would be encountered in a real plenum fire to observe poor behavior from traditional types of cable formulations.

They go on:

“In comparison to the plenum, the tunnel test is more severe.”

The above findings would seem to have been an indication that the NEC requirement for plenum cables was excessive and should be reduced. This, however, has not happened.

While we do not find a published report documenting this, it is also well-known that the UL 910 method is extremely sensitive to the mounting technique used for specimens. This creates two concerns: (1) reproducibility, and (2) validity. Under such circumstances, reproducibility can, nonetheless, be achieved if minutely detailed instructions are available for laboratories conducting the tests. With regard to validity, we have more serious reservations. When such a situation occurs where small specimen details can have great influences on final test outcome, the implication is that the range of actual fire behaviors is very wide and that the given test protocol captures only one of these very different possibilities. From a fire engineering point of view, this is an undesirable situation. It is preferable to obtain some more basic properties of the test specimen, ones which are independent of such scenario variations. Hazard predictions can then be made in a systematic way based on these properties and by assigning suitably conservative values to other problem parameters. This concept is further developed in chapter 8.

Finally, even though the UL 910 does not use the largest burner output (88 kW, versus 154 kW from the UL 1666 test, below), it is the most severe U.S. test for cables to pass. Kaufman [45] attributes some of this to the fact that the Steiner tunnel is well-insulated, whereas specimens in the vertical cable tests can more readily lose heat to the surrounding cabinet. The other critical question is the selection of the pass/fail criterion. The determination of this criterion for a specific test will determine the relative ranking of test severity. This is a normal function of a test method. However, even for a test which shows verisimilitude with actual conditions, the choice of the pass/fail criterion is not always straightforward. In a test which does not show verisimilitude with actual conditions, selection of a pass/fail criterion is essentially arbitrary.

The UL 1666 test for riser cables

The 1984 NEC introduced requirements on communications cables which are run in vertical shafts rising from floor to floor. Of all the cable testing methods surveyed, the resultant UL 1666 test method [47] most closely resembles an accurate, full-scale representation of a desired fire environment. The scenario considered [48] entails a series of telephone closets, located one above the other on adjoining floors. Test cables are strung through a riser shaft. The fire source selected was a propane burner with an output of 154 kW. The actual fire situation in telephone closets can entail a high fuel load during periods of construction or remodeling, when large amounts of both communications goods and packaging materials may be found in such closets. Thus, a 154 kW appears to be a reasonable ignition source for such a situation [49]. Further, the authors wanted to ensure that the ignition source itself would not cause fire propagation from floor to floor in the absence of cables. This is achieved by the test. From a technical point of view, this is an example of a sound, modern test. Its only shortcoming is that, being a real-scale rather than a bench-scale test, there are penalties of cost, difficulty, and reproducibility. Also, it does not provide data which would allow generalization of the results.

Since this is a full-scale test, validation against full-scale data is not needed. What is needed is to be assured that the ignition and scenario conditions selected were appropriate. We return later in this study to examine the question of ignition sources.

The UL 1685 test for limited smoke cables

In the 1990 NEC a new category was established. A large number of cables could be designated with an optional -LS designation, indicating they qualified as 'limited smoke.' The mandatory use of these cables has not yet been established. In response to this requirement UL developed a standard, UL 1685 [50]; this comprises the same equipment as used in the new IEEE 1202 test, but includes additional instrumentation. In the UL 1685 method, there are provisions made for running two types of tests: one where the burner exposure and the burn length criteria correspond to IEEE 383/UL 1581, and a second one corresponding to IEEE 1202/CSA FT-4.

The basic burner, ladder tray, and enclosure are identical to those used in the IEEE 1202 method. Instrumentation added include:

- duct-mounted photometer
- bi-directional velocity probe and accompanying thermocouple.

In addition, certain optional instrumentation are also identified:

- load cell for weighing specimen during test
- oxygen analysis equipment for measuring the heat release rate
- calibration equipment for calibrating the heat release rate measurement.

The same instrumentation for measuring smoke, heat, and mass loss is used for running either the UL 1581 or of IEEE 1202 exposure version (see below).

This instrumentation generally follows the guidelines set forth in the NORDTEST furniture calorimeter standard [51], at least in principle if not in all details. Especially, we note that the smoke measurements in this test are in appropriate engineering units, as discussed in reference [43].

The first draft of the test method [52] was accompanied by an appendix describing the results of the experimental program which led to its development. Twelve different cables, with a wide range in heat release rates, were tested using the UL 1581 type of exposure. Three out of 12 specimens were able to pass the requirements that were proposed initially:

- damage < 2.43 m above the bottom of the cable specimen
- peak smoke release rate $\leq 0.1 \text{ m}^2 \cdot \text{s}^{-1}$
- total smoke released $\leq 25 \text{ m}^2$

After a period of industry comments, the criteria were modified. The finally adopted criteria are:

for the UL-1581-exposure version

- damage < 2.43 m above the bottom of the cable specimen
- peak smoke release rate $\leq 0.25 \text{ m}^2\cdot\text{s}^{-1}$
- total smoke released $\leq 95 \text{ m}^2$

for the IEEE 1202/CSA FT-4 exposure version

- damage < 1.5 m above the bottom of the burner face (note that the mid-height of the burner is 14 mm above the bottom, but the mid-height is also 300 mm above the floor, so the difference between the bottom of the specimen and the bottom of the burner face is 286 mm; thus, the criterion corresponds to a distance of 1.786 m above the bottom of the specimen)
- peak smoke release rate $\leq 0.40 \text{ m}^2\cdot\text{s}^{-1}$
- total smoke released $\leq 150 \text{ m}^2$

The smoke criteria for this version are more lenient than the UL 1581 exposure version because the fire exposure itself is more severe in that version. Note, however, that the current edition of IEEE 1202 and of the CSA FT-4 tests do not include any smoke requirements (although such a requirement is eventually planned for IEEE 1202).

The HRR measurements made in the UL development program leading to UL 1685 will be discussed later in this report.

In aspects other than the inclusion of smoke, mass, and heat instrumentation, the two portions of this standard are identical to UL 1581/IEEE 383 for the first part, and IEEE 1202 for the second part. We will not repeat here comments made elsewhere for those two parallel tests.

3.2.1 General Comments on NEC Provisions

The NEC provisions grew during the course of quite a few years, driven by both fire safety concerns and commercial market positioning of various manufacturing interests. They are at the point now where some questions can be asked about whether the whole system should be rationalized. We make the following observations:

- The UL 1581/IEEE 383 vertical tray flame test is larger than bench-scale but smaller than actual fire scale. Thus, its results would require validation against actual fire scale testing. While some incidental and anecdotal testing results are available, a systematic validation is lacking.

- The smoke measuring procedures devised for UL 1685 are sensible and sound and represent one of the few instances so far where rational engineering units and computational smoke procedures have been introduced. The optional HRR measuring component of that test is also entirely consistent with current engineering state of the art.
- The UL 910 test presents unjustifiably severe and anomalous performance demands on plenum cables. There are two serious concerns with this test: (1) The severity of this test does not conform to normal engineering practice for building fire resistance requirements. Almost all building codes require significantly greater resistance against fire propagating floor-to-floor than they do for fire propagating horizontally within a single floor. The UL 910 horizontal-spread test is much more severe than the UL 1666 test used to assure that fire does not propagate along cabling floor-to-floor. (2) A validation effort *has* been made for UL 910 and demonstrated that the requirements are unrealistic and do not reflect actual plenum fire behavior.
- The UL 1666 riser test is of actual fire scale and represents a reasonable fire source and scenario.
- Further comments with regard to the use of bench-scale HRR test methods will be made in a later section.

Finally, we point out here that the NFPA National Electrical Code is applicable only to the United States. While we will review some of the Canadian test standards in detail, we do not examine the code provisions applicable in Canada. For this, users should consult the Canadian Electric Code [53]. Hartley and Jaques [54] have prepared a summary of some of the main features and some of the differences from the U.S. requirements. In general, while some of these tests have a connection with the situation that is to be protected, the pass/fail criteria remain arbitrary, and the tests do not provide sufficient information to perform analytic estimates of a fire hazard.

3.2.2 The ICEA 62 kW Test

As reviewed above, the view had been expressed from several quarters that a 21 kW exposure is insufficient and that a 62 kW exposure would better represent actual fires. This may or may not be true—the available documents examined did not prove sufficient to answer this question. Nonetheless, motivated by this concern, the ICEA developed a method whereby such a 62 kW ignition source would be used; this method has the reference number T-29-520 [55]. The main differences between this test and the IEEE 383 test are:

- Burner output of 62 kW.
- Burner location is 200 mm from the back of the cables and 300 mm above the base of the tray.
- The number of replicate runs to be done is not specified.
- The tray must not be closer than 0.3 m to any wall.
- A minimum ambient test temperature of 10 °C is specified.

- The specimen must be fastened to each rung by use of copper or steel tie wires no less than 1 mm diameter and no greater than 1.6 mm.

This test method has received a certain amount of use, but is not widely used or referenced. This test has yet to be validated against real-scale fires.

3.2.3 AT&T Cable Tray Tests

During the early 1970's, AT&T developed a vertical and a horizontal cable tray test, intended for use in testing wiring related to telephone systems. These tests [56] are now obsolete, so we do not intend to discuss them in detail. A technical history of these tests was given by Williams and Kaufman [57]. The main technical point pertinent to this history was the demonstration that flame spread along tray configurations where the cables are close-packed is significantly less than in an arrangement, such as the IEEE 383 test, where air spaces are present.

3.2.4 The New IEEE 1202 Test

To collect into one sequence the U.S. test standards, we discuss next the new IEEE 1202 test [58]. However, since the discussion will be making substantive comparisons to the Canadian FT-4 test, discussed below, the reader may find it convenient to first read the discussion on the FT-4 test.

The scope of IEEE 1202 is significantly different from its IEEE 383 predecessor, since it only covers a cable-tray fire test and has no wording dealing with nuclear industry applications. By contrast, IEEE 383 was specifically addressed to various aspects of electric devices for the nuclear power industry, and the cable-tray fire test was but one small portion of the standard.

- The burner is the same 21 kW burner specified in IEEE 383, although the metric conversion is rounded off to 20 kW. The 20 kW value is made mandatory, while the 70,000 BTU/hr unit is informational only.
- The burner is positioned at the same location as specified in the CSA FT-4 test,⁵ including the 20° angle.
- A concrete-masonry block test enclosure is described which is identical to the one shown in UL 1685.
- A forced-exhaust air movement system is required. The specification is derived from UL 1685, but more details are given. The exhaust duct flow is measured by the use of a bi-directional velocity probe and thermocouple. A rate of 0.65 m³/s is required prior to the start of test; this

⁵ The actual wording in IEEE 1202 is inconsistent as to whether the required height is to be measured to the top or to the mid-height of the burner face; private communication with the Chairman of the IEEE Working Group established that IEEE intended the burner height to be identical to the one prescribed in the CSA FT-4 test.

contrasts with the 5.0 m³/s used in UL 1685 test. In addition to the exhaust flow, draft velocities are controlled. The air velocity is not to exceed 1 m/s at the burner level and at the 1.5 m height along the cable tray position. This is in contrast to UL 1685, where < 1 m/s is mandated at the floor inlets into the chamber.

- The cable tray to be used can be the one used in the CSA FT-4 or one built according to a NEMA standard; the guidance here is somewhat more detailed than in either IEEE 383 or in UL 1581.
- The length of the cable tray and of the test specimen are to be exactly 2.4 m.
- An entirely new requirement for selecting specimens for testing is provided. To qualify a product line employing identical materials, (a) the minimum-size cable and (b) the cable having the highest nonmetallic/metallic ratio, by mass, are to be tested.
- The cable grouping on the test tray follows closely the specifications in CSA FT-4. The main difference is that it is not mentioned that cable placement should be restricted to the center 250 mm portion of the tray.
- It is specified that cables are to be attached to each rung, using copper or steel tie wire not larger than 2.08 mm².
- A new requirement is made for the number of replicates to be tested: two on the minimum-size specimen, and two on the highest mass ratio specimen.

3.3 Illustrative Military Requirements

There is a very large number of military specifications dealing with electric wire and cable. We will examine here several of the most commonly used ones. All of these specifications were developed by the Navy, but may be used by other military services. The most common, baseline specification is MIL-C-915F (Cable and cord, electrical, for shipboard use, general specification for). For more demanding applications, MIL-C-24643 (Cable and cord, electrical, low smoke, for shipboard use, general specification for) is common. Within each military cable standard there is provision for a large number of actual part numbers, each prescribed by a different 'slash number' and denoted with the main standard number, followed by a dash number. Here, we will only examine the requirements in the main specification and not look in detail into which dash numbers do or do not require a certain test to be used.

Several of the standards listed below also stringently regulate the emission of acid gases or other products of combustion; discussion of these provisions is outside of the scope of this review.

MIL-C-915F

There are three fire tests provided in this specification [59]. One part of this specification calls for the use of the IEEE 383 test, already discussed above.

Since the IEEE 383 test does not examine circuit continuity under fire, a 'gas flame test' is used for this

purpose. This test is not a common engineering test, but, rather, is described in detail in the military specifications. A 1.22 m cable specimen is held vertically in a cabinet. The source of fire is a ribbon burner fired at a power level of 8.3 kW. The length of time that the flame is applied is dependent on the 'dash number' for which it is intended. Further prescriptions are made for an electrical circuit to monitor the continuity during the exposure.

The final test is a 'weld spatter' test. For this test, an 0.46 m long cable specimen is held vertically, supported at the bottom by a special cup held in the jaws of a lathe chuck. A helically wound heating coil is positioned surmounting the specimen, near the bottom. Two spark plugs are situated a short distance above the heating coil. The test assembly is mounted in a small test enclosure which is provided with forced ventilation. The ignition time, burning time, and maximum flame travel distance must be within certain limits for the specimen to pass.

MIL-C-24640

This specification [60] prescribes two fire tests: the IEEE 383 test and the 'gas flame' test discussed above.

MIL-C-24643

This specification [61] cites the same two fire tests used by MIL-C-24640. In addition, since it is a 'low smoke specification,' MIL-C-24643 references the British Naval Engineering Standard NES 711 for smoke. This is curious since NES standards cannot be obtained from the British government and are, instead, "not to be released to the public." This means that U.S. contractors supplying cables according to MIL-C-24643 to the U.S. Department of Defense must obtain a specification which they are not allowed to obtain. We discuss the NES 711 standard under other countries' standards, later. The MIL-C-24643 specification also references another British standard, NES 713. This standard is a Draeger-tube method for determining the 'toxicity' of a specimen; toxicity testing is outside of the scope of the present study, however. There are indications that the NES 711 and 713 are being dropped by the British, and perhaps should also be replaced in the U.S. test suite.

MIL-W-22759E

This specification [62] deals exclusively with fluoropolymer-insulated wires. It contains a flammability test requirement and one for smoke.

The flammability test involves stretching an 0.61 m long wire specimen at an angle of 60° up from the horizontal. It is placed in a test chamber which is not enclosed, but rather, is open at the front and on the top. Ignition is by means of a Bunsen burner equipped with an elongated flame spreader. The Bunsen burner is placed perpendicular to the axis of the specimen, and with the long dimension of the flame spreader paralleling the specimen. Gas flow rate is not specified, but the blue flame is required to be 50 mm long and to indicate a 955 °C temperature. The flame is applied for differing lengths of time, depending on the gauge of the wire being tested. The specification does not contain any mention as to why a Bunsen burner test was developed which is different from existing Bunsen burner tests.

The smoke test is even more individualistic. A 5.25 m length of wire is suspended in a still-air room with 3.05 m of it being horizontal, while the remaining portion hangs vertically and is weighted down. A current is passed through the wire to heat it to its rating temperature (which depends on the ‘dash sheet’). The test criterion is that the current should be maintained for 15 min without any visible smoke being seen against a flat-black background. No details of room illumination are specified with this test.

Future trends for military specifications

The Navy has formulated a program focused on fuel load reduction on board ships. Since electric cables comprise a very major fraction of this fuel load, an effort is going on to reduce the fuel load of future cables. Over the next 5 years, the Navy has stated its intention to minimize reliance on some of the poorer currently-used bench-scale tests (such as NES 711) and to focus more on larger-scale testing. Eventually, the need is seen to implement HRR-based procedures, both in large and small scale. A definite strategy has not yet been evolved to reach this objective.

3.4 FMRC Tests

As we discuss later, there is a growing consensus within the fire research community that HRR-based testing for electric cables is the best way to obtain usable data on cable flammability. Factory Mutual Research Corporation (FMRC) was one of the pioneers of developing laboratory and large-scale methods for HRR testing. We discuss this early FMRC work together with other HRR studies later in this report. In this section, we discuss the test method which FMRC is currently imposing on their insureds.

In 1987 FMRC summarized the flammability provisions of the NEC and pointed out that a different, mutually incompatible, rating system could also be devised [269]. Unlike most testing organizations, FMRC is in a unique position since they are major insurers of industrial occupancies. Those companies wishing to be insured by the FM system need to conform to various of their guidelines. Non-conformance could result in either being dropped from the system or suffer premium increases. Thus FMRC can promulgate fire tests which have a wide-ranging impact. A negative factor to be considered, however, is that FMRC also functions as a testing, labeling, and certifying laboratory.

As described in the HRR section below, originally FMRC testing was done according to standard engineering principles of making HRR measurements. This would have enabled such testing to be conducted at more than a hundred laboratories that contain one type or another of bench-scale HRR apparatus. Unfortunately, the FMRC cable test standard was developed despite concerns of the wire and cable industry [63]. The test evolved from a HRR test into a scale-model cable test which does not measure basic HRR properties, but rather is fully apparatus-dependent on the exact configuration of the test rig, and available only at the FMRC.

This FMRC standard was published in 1989 as Specification Test Standard—Cable Fire Propagation (Class Number 3972). The test has two Phases. In Phase 1, a single piece of cable, 127 mm long, is placed horizontally on the load platform of the test apparatus and is exposed, progressively, to various specified irradiances. In this Phase, an irradiance vs. time curve is produced. Unlike normal testing in heat release rate apparatus, a designated specimen holder is not filled with lengths of specimen; rather, only a single specimen length is exposed. A Thermal Response Parameter is obtained by plotting the data

of ignition time (t_{ig}) versus the irradiance (\dot{q}_e'') as:

$$t_{ig}^{-1/2} = \frac{\dot{q}_e''}{\Delta T(k\rho C_p)^{1/2}} - a \quad (1)$$

where $\Delta T(k\rho C_p)^{1/2}$ is the Thermal Response Parameter (TRP).

In Phase 2, a single piece of cable, 0.61 m long is mounted vertically in the apparatus. A horizontal-plane irradiance of 50 kW/m² is set at the bottom of the specimen, but the specimen itself sees a somewhat different value, since it is oriented vertically. The upper portions of the specimen, of course, see a progressively smaller irradiance. In this Phase, the combustion atmosphere supplied is at 40% oxygen. The heat release rate is measured over a specimen which is simultaneously undergoing flame spread and non-uniform external heating. A Fire Propagation Index (FPI) is then computed as:

$$FPI = \frac{[0.40 \dot{q}_{peak}'' / \pi D]^{1/3} \times 10^3}{TRP} \quad (2)$$

where \dot{q}_{peak}'' = peak HRR (kW/m²), and D = the cable outer diameter (m).

Cable performance is then classified into one of three groups:

- Group 1: FPI < 10
- Group 2: 10 ≤ FPI < 20
- Group 3: FPI ≥ 20.

Technical analysis of the FMRC standard

- Elevated oxygen testing conditions

The use of an air stream containing 40% oxygen would appear on first blush as unreasonable for testing materials or products which are to be used in an environment where the oxygen concentration is 21% or less. The rationale is that the augmented-oxygen test condition simulates the burning behavior of very large pool fires, with diameters of several meters and heat release rates in the megawatts. As with all test methods, one must ask whether the scenario measures properties that are relevant to the situation to be standardized, then whether it is a sensible scenario, and finally, whether the pass/fail criteria are justified.

First, the FMRC development work [64] was done almost exclusively with base polymers and liquids. No data were reported which would explore the range of commercial fire retardant systems possible, combined with base polymers to which they are applicable. Oxygen augmentation can affect the flames from different polymers in very different ways—compare, for instance, the data of Aseeva [65] for polypropylene, versus the data of Khalturinsky [66] on PMMA. Flame retardant systems will also vary greatly in their effect as the thermal environment is changed. The result of these effects will be a preferential bias for one type of polymer/FR-agent system, versus another. This is not desirable. What is needed is a moderate external flux to be imposed on the specimen, and no increase over ambient oxygen conditions.

Second, the NEC tests go up to a maximum of 154 kW. This is vastly less than the 1.7 MW which a not-yet-optically-thick, 1.0 m kerosene pool fire will produce. In fact, as we shall see on the section on HRR, successful prediction of the results from present-day, industry-accepted, tests require external heat fluxes of 20 to 40 kW/m² to be imposed on the specimen, and **NO** elevated oxygen. No risk-based justification has been offered by FMRC to justify such a vast increase in the harshness of the test conditions. Thus the scenario appears not to be sensible.

- The concept of ‘Fire Propagation Index’

The ‘Fire Propagation Index’ concept is set forth in the FMRC back-up document on their test method [67]. The derivation begins with standard textbook concepts of flame spread. However, the results are not expressed in terms of accepted engineering practice. For instance, in the use of HRR quantities, it is important that (1) the irradiance on the test specimen correctly represent the external heating expected during the fire scenario being considered and (2) The bench-scale HRR results are meaningful only if the irradiance over the exposed face of the specimen is very nearly constant. The actual measurement conditions within the FMRC apparatus deviate radically from these requirements. In consequence, they obtain an equation for velocity of flame spread which may be dimensionally correct, but where the values of the various terms bear no relation to the theory itself.

The Fire Propagation Index is intended to represent the square root of the flame spread velocity. Even if this Index would correctly capture the essence of this velocity, such a velocity does not capture the essence of *fire hazard*. We discuss further (in the section on HRR) what is needed to obtain a true measure of fire hazard.

- Concerns with the assumed functional relationship for the TRP

A recent Sandia Laboratories study [68] examines the FMRC procedure for deriving the TRP. The procedure used by FMRC assumes a linear relationship to hold at all values of incident flux. The Sandia study points to examples of cable specimens where the relationship is distinctly non-linear at lower fluxes. In this study, Nicolette and Nowlen point out that data in the original FMRC studies leading to the method [69] show curves for piloted ignition and unpiloted to cross over. That result would imply that over a certain range of fluxes a specimen is easier to ignite if the pilot is removed which is not correct.

The most curious and controversial aspect of the development of this test method comes in a recent paper in which Tewarson and Zalosh [70] suggest that the ignitability and heat release rate data comprising the Fire Propagation Index can also be obtained from standard specimen tests conducted in HRR apparatus such as the Cone Calorimeter or the OSU apparatus. Tests run at ambient atmosphere on uniformly-heated specimens should give results different from those run at the conditions specified in the FMRC standard. If the results of one method could be derived from the other, then the more difficult and controversial test should not be needed.

Industry concerns with the FMRC standard

The usual procedure in developing a test method or standard is through consensus. This test method was developed without substantive changes based on input from industry or other concerned parties. As a result significant dissatisfaction has been voiced by industry representatives over various aspects of the FMRC rating scheme [63]. The concerns could be grouped into two areas: (a) the need for the test (i.e.,

the existence of other tests which provide better indication of performance); and (b) technical problems with the test (i.e., testing in enriched oxygen).

The issue of the necessity is quite crucial. While the FMRC made presentations on the point that their cable-related losses have been increasing, there has been no breakdown of data given to indicate that the loss problem is associated with cables qualified under IEEE 383. It seems inappropriate to condemn the adequacy of IEEE 383 if data are not available to show that unacceptable losses are being sustained with cables that have successfully qualified under this test.

The most serious of the technical problems noted by industry [63] is that full-scale validation efforts have been inadequate and that the performance of *no* Group 2 cables were ever verified in full-scale testing.

4 Methods in Other Countries

4.1 Canadian Tests

4.1.1 Ontario Hydro cable tray test

Wide use has been made of a test method developed by Ontario Hydro [71]. The main importance of this test method is that it was the basis for the CSA FT-4 test. Most of the changes made were to increase the reproducibility of the test. The test was made more difficult to pass also, since the flame travel distance allowed was reduced. Since it is very similar to the CSA FT-4 test which is described below, we point out here only those points on which this test differs from the CSA FT-4:

- A detailed procedure and a calibration jig are provided for doing a temperature calibration on the burner.
- No minimum ambient temperature specification for testing is made.
- It is required that no part of the cable tray be closer than 0.3 m to a wall.
- The minimum specimen length is 2.7 m, not 2.3 m.
- Tie wires must be used at least every 0.3 m, not every 0.45 m.
- The middle 0.15 m, not 0.25 m, portion of the tray is used for cables; also a somewhat different loading scheme is used.
- The minimum performance necessary to pass the test is not indicated; this is left up to actual procurement documents.

The burner angle in this test was set at 20° so that the flame would impinge approximately equally on both sides of the test specimen. This was felt to be more desirable than the situation occurring in the IEEE 383 version, where the flame flow pattern is such that only one face of the specimen is engulfed in burner flames. The 20° angle does serve to make the test exposure more than in the IEEE test.

The Ontario Hydro test also contains provisions for an indirect measure of corrosivity by measuring the total acid gas production. This test method is analogous to the CEGB method on corrosivity. Approximately 0.5 g of a cable insulation are introduced into a tube furnace and decomposed at a temperature of 900 °C with an air flow of 0 to 200 ml/min. The decomposition products are bubbled through a series of water/NaOH traps. The acid content of the traps are determined by titration after the test. The acid gas by-product can not exceed 14% by mass of the test sample.

4.1.2 CSA Tests

The Canadian Standards Association methods tend to be very similar, but not identical to corresponding U.S. methods. Since the signing of the Canada—United States Free-Trade Agreement [72] the National Fire Protection Association and CSA have formed a Binational Correlating Committee on Electrical Codes. While there is a certain similarity already between the CSA tests and UL tests, the work of this body could result in U.S. and Canadian Standards moving even closer together in the future.

The CSA establishes six fire tests for wires and cables, labeled FT-1 through FT-6 [73]. These are the following:

FT-1 Vertical flame test [similar, but less severe than the VW-1 test]

FT-2 Horizontal flame test [rarely used]

FT-3 Burning particles test [rarely used]

FT-4 Vertical cable tray test

FT-5 Flame test for mining cables [only of specialized application]

FT-6 Steiner tunnel test [identical to UL 910]

The CSA 'FT-4' test

Most of the CSA tests are in wide use only in Canada and will not be reviewed here. The FT-4 test, however, has been widely used in the United States and so will be examined in detail. American cable makers can run the FT-4 test to qualify their cables both under the CSA requirement and where IEEE 383 is required. Since the FT-4 test is more difficult to pass, the converse is, of course, not possible. The CSA cable tray was initially released in 1984 as an interim Electrical Bulletin No. 1426 [74]. This Bulletin is now obsolete, as its features were incorporated into the main C22.2 No. 0.3-M1985 standard in 1985.

Comparing against the similar IEEE 383, the main differences are:

- A cabinet enclosing the rig is mandatory; a forced air exhaust must be at a minimum of $10 \text{ m}^3/\text{min}$. To minimize draft effects, a maximum air velocity of $1 \text{ m}\cdot\text{s}^{-1}$ with the burner off is specified.
- A minimum temperature of the rig (5°C) is specified.
- The length of the ladder tray is 3.0 m, not 2.4 m, since ladders of this length are more commonly available.
- The burner orientation is 20° above horizontal, not horizontal-impinging. The mid-height of the burner face is positioned to be 300 mm above the bottom of the tray (with the tray bottom also being the bottom of the specimen and the top of floor).

- The length of the test cables is specified to be at least 2.3 m.
- Cables must be fastened with wire ties to the rungs of the ladder at least every 0.45 m; surprisingly, the IEEE 383 is silent on the question of how to attach the specimen.
- Different cable loading instructions are given. Unlike the IEEE 383 or the UL 1581 tests, cables with diameter < 13 mm are grouped into groups; this leads to more severe test conditions for thin specimens. Depending on the cable diameter, each bundle is to contain 1, 3, 7, or 19 cables. The tray, in turn, is to hold anywhere from two single, large cables, up to 13 bundles of grouped smallest-size cables. The center 250 mm of the tray is allocated for filling with cables.
- A screwdriver is to be used to find the limit of char damage after test; a maximum char length of 1.5 m above the bottom edge of the burner is permitted.
- No alternative ignition sources are allowed.

We will not parse the methods side-by-side here, however, we wish to make one important observation: It appears to be possible to successfully conduct the CSA test solely by studying the test description. It would probably not be possible to conduct the IEEE 383 test only by reading the document, without extensive consultation from other laboratories, and expect to obtain reproducible results. Thus, in comparing the two tests, we can summarize that (a) certain features of the CSA test represent genuine improvements in testing technology, serving to make the test better-defined and more reproducible. (b) The test is more difficult to pass, since the allowable damage distance is smaller. (c) Other features, such as the burner angle and the tray length, appear to be substantive differences from IEEE 383. Interestingly enough, UL has conducted a comparative study of a number of cables being tested in the IEEE 383 configuration and in the FT-4 configuration [50]. For the data set examined, the results did not show any systematic difference in product performance between the two methods. This would have to be verified with a substantially larger data set before a conclusion of ‘no statistical significance’ could be made.

4.2 European Developments – General

Tests used in several European countries are discussed individually below. Unlike in the United States or Canada, the IEC international standards have recently assumed a dominant role in European fire testing; these are reviewed at the end of this chapter. For the sake of comprehensibility, however, we will discuss here some of the general European developments.

Concern over flammability of cables used in cable trays first arose in Europe in June 1967 in Italy, when a substation belonging to the Italian utility ENEL in La Spezia sustained a serious cable fire [75]. In that very same year an Italian standard was issued for cable tray testing. The test could be performed at only one institution, Centro Elettrotecnico Sperimentale Italiano (CESI), which is located in Milan.

In subsequent years, cable fires of varying severity were experienced by other European countries, for instance, the 1979 fire in Britain at the Tilbury power station of CEGB. The general response has been to commission testing at CESI and to adopt for use in power plants only cables passing such a test. We review some of the details of this test in the section under Italy, below. As an example more accessible to North American audiences, we follow the application of this Italian test to testing in Great Britain.

During the late 1970's and early 1980's the *de facto* standards pertinent to much of the British cable making industry were the specification laid down by the British Central Electricity Generating Board (CEGB). CEGB has since been privatized, renamed National Power plc, and is no longer active in cable flammability research. During the above time period, however, a substantial amount of research was commissioned by CEGB and by the British cable makers and conducted by the Fire and Materials Laboratories of Queen Mary College in London. Part of the program comprised a comparison between the results of the CESI test and the IEC 332 Part 3 test, as it was originally proposed in draft form. The results were successful and indicated that very similar results could be obtained on the simpler IEC rig, without needing to resort to the unique CESI apparatus. With that, the CEGB no longer required that testing be done at CESI but permitted, instead, testing according to IEC 332 Part 3 to be done in the UK at Queen Mary College.

4.3 British Standards

4.3.1 BSI Standards

The main standards of the British Standards Institution applied to wire and cable are the following: BS 4066, BS 6387, BS 6724, and BS 6883.

BS 4066

This method [76] has three parts, which correspond, respectively, to the international standards IEC 332 Part 1, 332 Part 2, and 332 Part 3, discussed below.

BS 6387

The test [77] is intended mainly to rate cables to be used for fire alarm wiring, emergency lighting circuits and other applications where continuity must be preserved during fire. The stated purpose is where “cables are intended to be used for wiring and interconnection where it is required to maintain circuit integrity under fire conditions for longer periods than cables having conventional insulations such as rubber and PVC.” This test includes both non-fire serviceability procedures and fire-test procedures. The fire-test procedures are in three parts:

Section 10.1 *Resistance to fire alone*. This part is primarily a circuit integrity test. A horizontally oriented, 1200 mm long cable specimen is electrically energized and subjected to heating from below by a 610 mm tube burner using propane and pre-mixed air. For different rating categories, three different fire temperatures are to be established at a monitoring thermocouple: 650, 750, or 950 °C. Neither the fuel nor the air flow rates to the burner are prescribed, with both to be varied as need be to achieve the required thermocouple reading. The main failure mode is shorting out during test.

There is currently proposed a revision to this section of the standard. The revision being considered would provide for more reproducible temperature control and would also specify the exact burner gas and air flow rates to be used.

Section 10.2 *Resistance to fire with water*. This involves a 1500 mm long, horizontal cable specimen being heated by gas burners, while at the same time being deluged by sprinkler spray. For this procedure, four small slot burners are used, instead of one long one. A thermocouple reading of 650 °C is specified. It would appear that no pre-mixed air is used in this procedure. The cable is first exposed to only fire for 15 min, then exposed to flame plus water for another 15 min. The specimen must maintain circuit integrity for the total 30 min. There appears to have been no data published giving any evidence water sprinklers can worsen the performance of cables in fires. So this test would seem to be at variance with actual degradation scenarios.

Section 10.3 *Resistance to fire with mechanical shock*. The test cable is burnt and shaken at the same time. Again, there appears to be an issue of validity for this test. A test which imposes fire and mechanical loads at the same time is a *thermostructural* test. It is well-known that degradation due to heat and the bearing of load do not scale according to the same geometric principles. This is the reason, for instance, why the basic ASTM E 119 [78] test for fire endurance requires loaded members to be tested in a real-scale furnace and does not permit bench-scale testing. Performing thermostructural tests on bench-scale samples is considered, in light of current engineering knowledge, to be invalid. Also, failure of circuit integrity is associated with the way that cables are tied down and permitted, or not permitted, to deform under actual fire conditions. Again, this cannot be represented in a bench-scale test.

Once all the burning, water spraying, and shaking has been completed, a cable can qualify for one of the following letter symbols:

- A resistance to fire alone, at 650 °C for 3 h
- B resistance to fire alone, at 750 °C for 3 h
- C resistance to fire alone, at 950 °C for 3 h
- S resistance to fire alone, at 950 °C for 20 min
- W resistance to fire and water, at 650 °C for 30 min
- X resistance to fire and mechanical shock, at 650 °C
- Y resistance to fire and mechanical shock, at 750 °C
- Z resistance to fire and mechanical shock, at 950 °C

No repeatability or reproducibility data could be found on this method in the published literature. It is especially surprising that both fuel and air flows to the burner may be adjusted freely, providing only that the desired thermocouple reading is achieved. A test where two degrees of freedom of adjustment are available but only one restraint condition is laid down appears to be inadequately standardized.

BS 6724

This is a general specification [79] for cables exhibiting reduced emissions of smoke and corrosive gases. The corrosivity specification involves solely testing for HCl emission. It has been shown that HCl is by no means the only corrosive product of importance that can be produced from burning polymers [80]; we will not consider other problems of corrosivity measurement within this review, however. This BSI specification is mainly notable for the fact that it comprises the first standardization of the '3 metre cube' test for smoke production from electric cables. The 3 metre cube method was originally developed by Garry Duggan, then of the London Transport Executive [81]. This test has, of late, become very common in Europe, and is discussed in detail under IEC 1034, below.

BS 6883

In the current version [82], this specification only required that BS 4066 testing be done; in the next revision, however, the 3 metre cube test is also slated to be added.

4.3.2 NES Standards

The British Department of Defence has a series of Naval Engineering Standards, some of which have been applied to cable specifications not only in the UK, but also by the U.S. Navy. The most important of these is NES 711.

NES 711

The NES standard [83] is based on the NBS smoke chamber (ASTM E 662), but with certain modifications. The modifications consist of the following:

1. A mixing fan is installed in the chamber to stir the combustion products. This procedure is questionable since there is a recent British study [84] which demonstrates that the use of stirring fans inside a closed-box type of smoke chamber cause poorer, not better quality data to be obtained.
2. An additional heater is introduced into the chamber to shorten the warm-up time.
3. A different burner is used to ignite the specimen. This is not surprising, since there has been a significant amount of user dissatisfaction with the standard burner used in ASTM E 662. For instance, the aviation variant of E 662 (numbered F 814) provides for an alternative burner type.
4. The method of calculating results is changed.
5. Additional instructions are given on how to prepare and mount wire/cable specimens.

The reasoning behind some of these modifications has been set forth by Routley and Skipper [85]. The expanded instructions for preparing wire/cable specimens are obviously desirable and a natural evolution. The other points are unproven to be improvements. Of more concern, however, smoke data in general from the NBS smoke chamber suffers from a number of limitations [117]; these are solved in more current methods, discussed later.

NES 713

This method [86] is described as a 'toxicity index.' In actual use, it functions as a screening tool to address the British Navy's concerns about corrosivity and is used where low-halogen products are desired. The method comprises an 0.7 m³ box in which a Tirrill burner is placed in the center. Actual wires or cables are not tested; rather, small plates of polymer material containing 1.5 to 2.0 g of combustible are required. During the test, 12 different gases are measured by Draeger tubes. The end result comprises a 'toxicity index,' whereby actual measured concentrations are divided by values of the LC50 for each gas. This procedure has two problems: use of Draeger tubes for quantitative work is condemned by

ASTM [87] as lacking in accuracy. Of more serious concern is that the values of LC50 mandated for HCl, HBr, and HF are about an order of magnitude lower than their true values. Since the same conservatism is **not** shown with regard to other toxic gases, the net result is a method functioning primarily to exclude halogenated products.

NES 518

This method [88] directly determines acid gas content. Section -0408 cites a requirement to measure the acid gas content of general purpose sheathing for electrical cables. The sheathing material is tested for acid gas content by using the Lassaigue Test (Sodium Fusion Test). This test uses approximately 0.25 grams of cable insulating material. A note in the standard states that “the test is to show a negative result for halogens.” This test method measures the acid gas concentration of the decomposition products. Corrosivity is not directly measured.

4.3.3 CEGB Standards

Prompted by losses experienced in a number of European power stations, CEGB focused on testing requirements for cables which would be more strenuous than those provided in BS 4066. It was especially seen that a serious hazard could result when cables are used in a high packing density, as opposed to single cables. In the late 1970’s the main facility available in Europe for providing a strenuous test of cables was a vertical tray test developed at CESI. Based on this apparatus, CEGB developed standard GD CD 21. The standard was then referenced in two cable specifications, one for PVC-containing cables and one for non-PVC cables.

GD CD Standard 21

This standard [89] is based on using the CESI test rig. The rig comprises a vertical chamber, 750 mm by 750 mm in plan and at least 2.5 m high. Air is admitted to the chamber by means of a 750 mm × 250 mm opening at the bottom. There is no fan and natural convection is relied upon. The cables are mounted on a steel cable tray which is at least 2.5 m high and 300 mm wide. The tray is mounted centrally within the test chamber. In actual practice, the CESI rig exceeds this standard by providing a 4.5 m high chamber; typically the length of cable tested is 3.5 m, not the minimum of 2.5 m.

Cable loading is prescribed to be 10 kg combustible/m tray length. Power cables are attached individually, with 25 or 35 mm gaps between each. Control cables are mounted touching, with no gap.

The ignition source is not a burner but, rather, two radiant heating panels, which may be either fed by gas or electricity. The panels are to be 700 mm high and must be (the two together) at least 50 mm wider than the cable specimen at each side. The panels are mounted on a pivot arrangement. A small gas pilot burner is placed above each panel to ignite the pyrolysis vapors.

The operation of a test under this procedure is very unusual and is untypical of any other test. The radiant panels are first preheated to reach an operating temperature. Then they are swung into place facing the specimen and maintained in this position for 1 h. No definitive prescription of panel temperature or heat flux is made. Instead, the requirement is that a panel temperature be selected such that ignition of the specimen results within 15 min of the start of exposure. However, a temperature > 600 °C must be used

in all cases. If the specimen fails to ignite, then a new run is made on a fresh sample, doing this until the correct condition is reached.

The specimen fails if flame damage extends more than 1.5 m above the top of the radiant panels.

A calibration standard is provided for, consisting of certain cables which are required to be tested and required to fail the test if the apparatus is properly operated.

This test is highly unusual in that more fire-resistive specimens are challenged by a more difficult exposure. Most other fire tests are geared towards providing uniform test conditions for all specimens. Enough information is, unfortunately, not available in the literature to be able to judge the reasoning that went into the design of this test procedure.

In addition to the vertical cable tray test, GDCD 21 also prescribed an oxygen index test. The purpose of this test was not to qualify a cable for use. Rather, by requiring that oxygen index results be obtained on the samples along with the cable tray results, a scheme for quality control was set up. Later, production lots were to be checked for variation against the qualifying value of the oxygen index.

Specification E/TSS/EX5/8055 (for PVC cables)

This specification [90] was based on a research work that had been conducted by CEGB on characterizing fires with PVC cables. The CEGB studies especially focused on cable loading. This led them to conclude that the mass of PVC per length of cable (or cable bundle, if bundled) was the critical factor. Their 'Critical Mass theory' was expressed as: "whereas cables using PVC would not burn [in the BS 4066 Part 1 test] when the source of ignition was removed, when the quantity of cables in any one cross-section exceeded a certain weight of PVC then propagation would occur once the cables had been ignited. Although no precise figure of the critical mass of PVC is possible because this can vary with the PVC compound utilized and the amount of space between individual cables, it is now generally accepted that the critical mass is in the order of 2-3 kg/metre."

This specification originally only allowed testing to be done in the CESI rig. Since its location in Italy was, naturally, inconvenient to British cable companies, a research program was carried out to determine if similar results could be obtained in the simpler IEC 332 Part 3 rig, one of which was located at the Queen Mary College Fire & Materials Centre in London. The results [91],[92] of comparative testing in the CESI rig and in the IEC 332 Part 3 rig show similar pass/fail ratings for various test cables. As a part of that same study, it was verified that, all other factors being equal, increasing the loading density for PVC cables increased the damaged length, although the magnitude of this effect varied according to cable type. A further comparison of various bundling arrangements against loading density suggested that the effects of changes in the bundling arrangement could be much more dramatic than those due to increased combustible loading.

Thus, as a result of the above research work, in the 1983 edition of the specification, in addition to allowing testing in the CESI rig, it was specified that the IEC 332 Part 3 test may be conducted, but the test must be run at the Queen Mary College laboratory. The latter restriction stemmed from the fact that much of the CEGB development work had been done in that laboratory and that data were not available to indicate whether interlaboratory reproducibility of the then-new method would be adequate.

For tests conducted in the IEC 332 Part 3 test, Category A loading had to be used. The test was modified, however, with the following requirement: *“during the test penetration to the conductor shall be achieved on the row of cables nearest to the burner. Penetration is deemed to mean that the conductor insulation is consumed or degraded to ash. If penetration to the conductor is not achieved a retest on a new set of cable samples will be required with the ignition source increased to 2 [of the standard] burners.”* This requirement is similar to the philosophy used in conjunction with the CESI test, where better-performing cables are challenged with a higher standard.

Specification E/TSS/EX5/8056 (for non-PVC cables)

This specification [93] establishes 4 categories of cables: those having reduced fire propagation, those with low smoke emission, those with low corrosive gas emission, and those with low toxic gas emission. The latter two categories are outside of the scope of this review and will not be examined.

This specification is very similar in many respects to the PVC specification, thus only major differences will be highlighted. Unlike the PVC specification, three categories of flame tests are called out: BS 4066 Part 1, the oxygen index test, and the vertical cable tray test. Because of the later date of this specification, provision for testing at CESI is no longer made and all cable tray testing is required to be done at Queen Mary College using the IEC 332 Part 3 rig. Power cables are to be spaced with 20 mm clear spacing on the tray, while control cables are bundled rather than flush-set. For certain applications an additional requirement is made to test at 20 or 30 kg/m loading densities. In those cases, a 620 mm wide cable tray is used and two burners are used, mounted side-by-side in a straight line. The burner flame is applied for 40 min in all cases.

The failure criterion is the same as specified in IEC 332 Part 3.

The low smoke cables are qualified by the 3 metre cube test. The procedures of IEC 1034 are modified in that basically the complete IEC 332 Part 3 cable tray and propane burner assembly are substituted for the horizontal cable orientation and alcohol pan fire specified in IEC 1034. The cable samples, however, are only 2 m long and are loaded to a density of 5 kg combustible/m.

For quality control purposes, it is provided that the results of the Arapahoe smoke test (ASTM D 4100) or the NBS smoke density chamber are to be used.

4.4 Italian Standards

CEI 20-22

The first edition of the Italian cable test standard CEI 20-22 [94] was issued in 1967. It prescribed a single cable tray loading of 10 kg combustible material per meter of tray length to be used. The next edition was issued in 1973 and made two main changes: new methods for fixing cables to the tray were specified, and a second packing density was also permitted, 5 kg combustible/m tray. The current edition was published in 1989. It subdivided cables into PVC types and all others. PVC cables must be tested using the existing CESI test with a loading of 10 kg combustible/m tray. Non-PVC cables are permitted to be tested using IEC 332 Part 3. For the latter, the Category C (combustible loading of 1.5 L/m tray) is to be used.

The CESI test rig and way that the test is run have already been described above under the discussion of CEGB tests, thus here only some differences in specification and testing conditions will be summarized. While the CEGB standard permits either gas or electric panels, at CESI the actual rig uses electric panels. These panels consume 30 kW of electric power.

The length of cable to be tested is 4.5 m. If there is evidence of continued combustion, the test is not stopped at 60 min (when the panel heating is removed), but is rather continued until extinction, up to 120 min. The failure criterion is if damage exceeds 3.5 m above the top of the panels, as contrasted to the more severe 1.5 m in the CEGB standard.

It is judged by CESI [95], however, that future testing of electric cables in Italy will be moving over to the use of the Cone Calorimeter and HRR-based methods.

4.5 French Standards

NF X 70-100

This method [96] is similar to other procedures used to characterize acid gas by-products of the combustion of cable insulation materials. A tube furnace is employed to thermally heat a sample and water traps are used to capture acid gases. Analysis is conducted by titration following the combustion test. Tests are conducted on 0.5 to 1 g of material placed in the furnace. The furnace is heated to either 400 °C, 600 °C, or 800 °C. The sample is left in the furnace for approximately 20 mins.

4.6 Swedish Standards

Swedish standards are not well known nor commonly used in North America. We mention here one Swedish standard, however, because of its role in the evolution of an IEC standard discussed below.

SS 424 14 75 (1978 Edition)

This standard [97] provided for the classification of power cables into 4 classes, as follows (note that the standard does not define the scope or use of these categories—this is left to regulations or specifications):

Class	Requirements
F1	none; non-FR cables
F2	pass clause 5
F2	pass clause 6
F3	pass clause 7

The clause 5 test parallels IEC 332 Part 1.

The clause 6 test apparatus comprises a type of 'fire tube.' A vertical steel cylinder having a 125 mm diameter and 800 mm length is used. Six ventilation slits are located along the length of the cylinder. An 850 mm cable specimen is suspended vertically along the centerline of the tube. The cable diameter may be a maximum of 70 mm. For smaller diameter cables, a series of rules is given indicating when such small cables can be tested alone and when they need to be bundled into bundles of five or three. Ignition is achieved by means of an conical, ethanol-filled pan set a short distance below the (open) bottom of the steel cylinder. The maximum capacity of ethanol is 1 L, but the exact amount to be used, and also the time that the burning is to be stopped, are determined by a formula which takes into account the specimen diameter and the cross-sectional conductor area. A top lid is provided to the cylinder. This lid is held a certain distance above the open top of the cylinder. The exact distance to hold this lid is determined during a calibration procedure where the temperature is measured at a location 130 mm below the top of the cylinder. This is another 'screwdriver' method, in that the pass/fail criterion is whether the damaged zone comes to within 300 mm of the upper end of the specimen.

The clause 7 test is a vertical cable tray test. The ladder is made of galvanized steel and is 600 mm wide by 3.6 m high. The ladder is enclosed by a test enclosure which is 1.0 m wide, 2.0 m deep, and 4.0 m high. It is to be built of 'incombustible' material. The back face is insulated by a 65 mm layer of insulating fiber blanket. The test enclosure is placed on four legs, 150 mm high. The air flow is by natural draft, there being a 400 mm × 800 mm opening in the bottom of the enclosure and a 300 mm × 1000 mm opening at the top. The ladder is located 200 mm above the bottom of the enclosure and 150 mm away from the back wall. The ignition is by means of a tray containing 6 L of ethanol, placed below the specimen. Each cable specimen is 3.6 m long. The number of cables to be used is determined by a table which, basically, provides for there being at least 18 kg of non-metallic specimen content in the entire test cable array. Cables with a conductor area $< 2.5 \text{ mm}^2$ are mounted flush against each other, filling up a maximum width of 500 mm. If needed, more than one row is used. Cables of greater conductor area are mounted with an open space of 10 mm between each. If the required amount cannot be fitted into the 500 mm width, then they are grouped into triangles of three. The specimens are lashed with metallic fasteners on every second rung. The cable qualifies for an F4 rating if damage does not extend further than 3.0 m along the 3.6 m height.

SS 424 14 75 (1988 Edition)

This standard [98] was substantially re-written in light of the current editions of the IEC standards. Starting with the classification, in addition to a re-numbering of the clauses, certain substantive changes are seen:

Class	Requirements	Additional requirements
F1	none; non-FR cables	—
F2	pass clause 7	—
F2	pass clause 8	pass clause 7; this class is inapplicable to cables with an outer diameter > 35 mm
F3	pass clause 9	pass clause 7; separate tests needed for products with D < 35 mm and D > 35 mm

Clause 7 (old clause 5) again simply refers to IEC 331-1 and IEC 332 Part 2.

Clause 8 (old clause 6) is essentially identical to the 1978 edition. The main change is that this clause is now restricted to cables having a diameter ≤ 35 mm.

Clause 9 (old clause 7) was substantively altered in the new edition. It now parallels IEC 332 Part 3, except that the concept of Categories A, B, and C is not used. The procedures specified are solely pertinent to what comprises Category B in the IEC 332 Part 3 standard. The new Swedish standard specifies that the air flow rate through the cabinet must be maintained at the inlet to be 5 m³/min. It also gives specific details on how to compute the volume of combustible material being tested; these instructions are not given in the IEC 332 Part 3 standard.

4.7 Belgian Standards

Of note among the Belgian standards is the following test for the fire-resistive capabilities of electric cables. This method is of interest outside Belgium since it forms the basis of a requirement in the EC directive on fire safety. The latter is discussed below, under international standards.

NBN 713-020

The above standard is the general fire endurance test method used in Belgium. Addendum 3 [99], issued in 1990, provides for the fire resistance testing of electric cables. The test method is sometimes referred to as the 'EGOLF oven test.' It is used by the fire testing stations at the University of Liege and the University of Ghent. A standard wall testing furnace is used, with a 3 m × 3 m dummy specimen holding three cable trays, one above the other. The procedure uses the standard temperature-time curve set down in ISO 834 [100], with most other additional operating details being as specified in the main NBN 713-020 document. The testing of power, signalling, and telephone cables is provided for. The basic test is for circuit integrity, with three rating periods being provided: 30, 60, and 60 min. Instructions are also given requiring that the cable tray and tray support system be able to withstand 120 min fire without structural failure, but this is tested separately.

4.8 International Standards

The reader should note that all of the current European national test methods are being replaced by the IEC and ISO (International Organization for Standardization) methods described in this section as part of the harmonization of testing standards for the European Community. This will make these other standards obsolete. It also can be expected that the United States will eventually feel market pressures to comply with these IEC and ISO methods.

IEC 331

This test of for electric continuity under fire conditions [101] is patterned on a portion of BS 6387, namely Section 10.1 (resistance to fire alone). Instead of three alternative testing temperatures being allowed for, however, only testing at 750 °C is specified. It is intended to add the water spray and mechanical impact sections of BS 6387 (a circuit integrity test) at a later date.

The same changes being considered for BS 6387 are also being proposed for this standard.

Within Europe, there is currently a debate on whether a European norm for fire-resisting cables should be based on IEC 331 or on an alternative test. The alternative test being considered is the Belgian 'EGOLF oven' test, described above. There is some ongoing concern with the EGOLF oven method in that it appears to be not possible to successfully qualify armored cables under this method, nor ones where a thermoset sheathing material is used. The method appears to have a good chance to becoming a mandatory standard, since the Commission of the EC has required its use in its 'Interpretive Document' [102], Par. 4.3.4.6. In it, two testing regimens are outlined: use of the ISO standard temperature-time curve, with circuit continuity rating times of 30, 60, or 120 mins. Cables with conductor area of 2.5 mm² or less, however, are to be tested under a modified curve, the details of which are not given.

IEC 332 Part 1

This is a small burner type test [103] for a vertical wire or cable specimen. A specimen 600 mm long is exposed to a burner flame. The burner is tilted at 45° with respect to the specimen axis. Either propane with pre-mixed air or natural gas with no air pre-mixed may be used for the burner. Burner adjustment is specified by the total length of the flame and the length of the inner blue cone; these are both different for the two gases. The correct burner adjustment is verified by inserting a bare copper conductor of specified dimensions and recording the time required for it to melt, which must be between 4 and 6 s. The flame is applied for a time period which is greater than 60 s, the exact value being determined according to a formula based on the mass of the test specimen. A 'screwdriver' criterion is used for acceptance, in that the damaged portion must not extend 50 mm or closer to the point where the top of the specimen is clamped.

Revisions are also underway to this method. It has been found [104] that according to the present prescription requiring a variable time for flame application, cables using copper conductors are subjected to a flame for much longer than ones using identical polymer materials but an aluminum conductor. Thus, the proposed revisions base the length of time on the cable diameter, rather than the mass. Another problem identified with the present procedure concerns the testing of polyethylene-jacketed cables. Some such cables melt, drip, and burn *downwards*. This is clearly undesirable behavior, yet is not restricted

by the current standard which only regulates upward propagation. Thus, the revisions provide for also failing cables which have damage downward extending more than 540 mm below the lower edge of the top clamp. In terms of test hardware, the most significant change is the substitution of the 1 kW burner, described under IEC 695 below, for the old burner.

Functionally, the IEC 332 Part 1 method has some similarity to the UL 1581 VW-1 test, although it is generally considered to be less severe.

IEC 332 Part 2

This test [105] is a variant of the previous test, designed to cover cases where IEC 332 Part 1 results would not be valid because the area of the copper wire was so small that the copper melted out during the test. The test is similar to IEC 332 Part 1, except for the fact that the length of the burner flame is shorter; that only propane is permitted to be used; and that the duration during which the flame is applied is the lesser of: 20 s, or the time to melt the conductor minus 2 s.

In a parallel development with changes to IEC 332 Part 1, consideration is being given to replacing the present burner in this test with the 500 W burner of IEC 695, but definitive action has not been taken on this.

IEC 332 Part 3

This is the international standard [106] corresponding to IEEE 383. It came about as somewhat of an amalgam between features of the IEEE test and the 1978 version⁶ of the Swedish cable test SS 424 14 75. The burner is taken directly from IEEE 383. The cabinet is taken directly from the older version of the Swedish test. The main difference in the cabinet is that the older Swedish test specified a thermal insulating blanket only on the back of the cabinet, while the IEC 332 Part 3 also requires it along the two sides. The length of the test ladder is reduced slightly, from 3.6 m to 3.5 m, as is the corresponding length of the test specimen. The bottom of the ladder stands 0.4 m above the floor, but the specimen's bottom edge is at 0.1 m above the floor. The burner is located directly facing the front of the ladder, 75 mm in front of the cables. The flame is to hit the specimen at 600 mm above the floor.

Unlike any of the predecessor tests, three different cable categories are established in IEC 332 Part 3, identified as A, B, and C. The category determines the loading density to be used and the length of time that the burner is to be applied:

⁶ The current version of this Swedish standard is essentially identical to the current edition of IEC 332-1, 332-2, and 332-3.

Category	Loading density (L of combustible material/m)	Burner flame application time (s)
A	7.0	2400
B	3.5	2400
C	1.5	1200

The document itself does not explain where cables of different Categories are to be used. Instead, the Categories are used by various national or using agency specifications which call out the use of IEC 332 Part 3; there they would specify that for a particular cable specification the test must be run according to Category A, B, or C.

The criteria for passing, in all Categories, is that the flame damage extend no more than 2.5 m above the bottom edge of the burner.

The method states that a future change is envisioned whereby forced air flow conditions through the test cabinet will be specified, with a rate in the range of 4.5 to 10 m³/min being envisaged. By comparison, note that the 1988 edition of the Swedish standards specifies a flow rate of 5 m³/min.

The 1987 revision to IEC 332 Part 3 contains an appendix with an entirely new procedure—the limiting oxygen index (LOI) test. In the LOI test, rectangular plaques of polymer are tested, rather than fully made-up cables. The apparatus has been developed specifically for testing rectangular plaques, but is conceptually similar to ASTM D 2863 [107]. The procedure is not viewed as an additional or alternative requirement, but rather as a quality control (QC) check. The LOI procedure is much cheaper and simpler to run than is a cable tray test. A cable manufacturer can obtain the LOI value on the materials which went into his original cable that was successfully tested in the cable tray test. From that point on he can maintain a QC check by running LOI tests on new lots of material. The use of an LOI test for this purpose stems from the philosophy of the CEGB, as discussed above.

The IEC vertical cable tray test should not be viewed as a test being conducted under actual end-use conditions. Orientation, ignition source intensity, packing density, and a whole range of other factors may serve to make the test an insufficient representation of reality. For instance, after an intensive study of the standard test results, compared against variations where mounting methods and packing density were varied, Sydney-McCruden concluded [108] that “the use of cables which have met the requirements of IEC 332 Part 3 does not guarantee that the cables will not propagate fire when installed in a ship.”

IEC 332 Part 3 and CSA FT-4 are *qualitatively* interchangeable with IEEE 1202 but neither is optimum from an engineering standpoint for evaluating fire performance of wire and cable. Both suffer from the same limitations in design and instrumentation: unlike some of the currently available UL methods, they lack HRR and smoke measurement functions, and also are neither real-scale nor adequately validated.

IEC 695 Part 2-4

This document is intended to standardize some improved small burners, which can then be referenced by other IEC standards. The method is still in draft stage, with three Sheets being prepared. IEC 695 Part 2-4 Sheet 0 [109] provides general advice. One of its principal objectives is to improve the reproducibility of small burner test results, by laying down four requirements:

1. The burner must be based on good engineering drawings available to IEC.
2. Both the type of fuel gas and its exact flow rate must be specified; a high purity gas is required.
3. The air flow rate (for pre-mixed flames) must be specified.
4. Calibration procedures must be available.

These are all requirements which are, unfortunately, commonly lacking in most existing test methods.

The method encourages the use of pre-mixed flames, even though they are agreed to represent actual fire conditions more tenuously, since they are more controllable.

For calibration purposes, a copper block is specified to be used. The rate of increase in temperature of the block is used as the calibration control. The temperature range from ambient to 100 °C is excluded to avoid problems with humidity.

It is recommended that the time of flame application be fixed, and a number of standard flame times is given. Methods involving repeated application of flame are discouraged, due to the poorer reproducibility of their results.

To prevent debris from falling into the burner, it is recommended that an angle of 20° be used, instead of straight vertical.

Sheet 1 [110] provides details of a recommended pre-mixed flame burner operating at a 1 kW level. The burner was initially developed in the laboratories of ICI Ltd, in England. In conformance with the requirement of Sheet 0, the burner has two separate inlet flow connections, one for fuel gas and the second for air. The burner uses propane at a flow rate of 650 mL/min (23 °C, 0.1 MPa conditions) and air at a flow rate of 10 L/min, under the same conditions. Burners conforming to all of the details given in this Sheet will be permitted to be labeled "1 kW nom Test Flame Apparatus, conforming to IEC Publication No. 695 Part 2-4/1." Some of the development leading to the 1.0 kW burner has been described by Michel [111].

Sheet 2 [112] provides details on a pre-mixed flame burner to be operated at the 500 W level. Initially, it was proposed to use a propane burner for this purpose. However, it was found that methane gave better results. Thus, the draft specifies methane, but does permit certain countries having difficulties in procuring adequately pure methane to use an alternate procedure based on propane. The Sheet will be issued with provisions for two alternate burners: (1) the same physical burner as used for the 1 kW tests, which provides for the direct metering of air flow rate. (2) A burner based on the '5V test' of UL 94 [113], which uses a Tirrill burner having conventional adjustable air holes in the side of the barrel for air intake. The Tirrill burner used in that UL standard has in recent years been improved, but as a Tirrill burner still suffers from the problems of damageability and unreliability of the metering needle and orifice. Likewise, air inflow rates cannot be metered with the Tirrill burner. Air flow control is done, instead, by the requirement that the 'blue cone height is 40 mm.' The methane flow used to achieve

500 W is 965 mL/min. This dual-burner use situation has been seen to be somewhat less than fully satisfactory. As a result, a proposal has been made by the Japanese IEC delegation to use a hybrid burner. The hybrid burner has the base of the 1 kW IEC burner, the burner tube of the Tirrill burner, and an air manifold by which air can be metered in. A flame stabilizer is not used since it is not necessary at the 500 W level. It is expected that this Japanese burner design will be accepted in the next round of revisions.

It is the stated intention that a further Sheet be issued which gives details of a 50 W burner, but this work has not been completed. Such a 50 W flame would be similar to IEC's 'needle flame' or to the '20 mm flame' in UL94.

IEC 1034-1 and 1034-2

This is the IEC document standardizing the 3 m Cube smoke test. The standard is published in two parts. IEC 1034-1 [114] gives details of the test equipment.

The equipment comprises a cubical room, 3 m in each dimension. It is equipped with two stanchions, upon which cables are laid horizontally. Below the test specimen, a tray containing 1 L of denatured alcohol is placed. The room is equipped with a photometer, a stirring fan, and a screen which serves to prevent light from the flames from entering the photocell. IEC 1034-2 [115] prescribes the test procedure. The number of 1 m long cable pieces to lay down for a test depends upon the cable diameter and range from one piece (for $D > 40$ mm) to three (for $D \leq 20$ mm). This loading program corresponds to the relatively light combustible load of about 2 to 3 kg/m which is generally found in underground railway applications. The specimen passes if the minimum transmission measured by the photometer does not reach or drop below these values:

1 piece tested	70%
2 or 3 pieces tested	60%.

The standard contains several *caveats* to the effect that some of the details are provisional and may soon be changed.

The 3 metre cube is used in a modified form by the CEGB, because of the much higher combustible loadings found in power plants, compared to this situation in railways. Thus, the CEGB variant of this test [116] makes some changes. A vertical tray holding a cable load of 5 kg combustible/m is used instead of the horizontal arrangement. The ignition source is a propane burner instead of the alcohol pan.

The 3 metre cube was initially developed as an inexpensive approach to smoke testing. Viewed in the context of present-day smoke measuring systems, however, it appears to offer the cost and size disadvantages of large-scale testing, while combined with the unproven validity of a bench-scale test which has not been correlated to actual behavior of large-scale fires. Smoke production tendencies nowadays are assessed by first establishing specimen configurations and heating conditions which lead to a suitable representation of actual-fire conditions. In the 3 metre cube test, the 1 L alcohol source does not appear to simulate such fire conditions. Once such exposure conditions are established, a number of other considerations become important for measuring smoke correctly; these are reviewed in [117]. In general, we can say that, in this test the pyrolysis of the fuel is arbitrary and the smoke measurement equipment violates optical theory.

This test is specifically reviewed here because it has become the most popular method used in Europe for measuring smoke from cables. Its only advantage is its popularity; smoke can be measured much more appropriately in large-scale tests by methods such as incorporated into UL 1685 (see above), or in bench-scale by methods such as the Cone Calorimeter (see ch. 10).

ISO 10093

ISO Technical Committee TC61, which is concerned with plastics, has issued a standard, ISO 10093 [118] which describes a number of ignition sources used by various currently used test methods. This document serves to review the types of ignition sources which are used and is mainly an educational tool. As part of this review, this standard also discusses the 1 kW source of IEC 695 Part 2-4 Sheet 1.

5 Bench-scale Test Methods

In the previous chapters, standard reaction-to-fire test methods for wire and cable products have been reviewed. In this chapter those nonstandard or developmental tests that have been used to measure fire properties of wire and cable assemblies or polymers intended for use in wire and cable applications. Standard test methods are mentioned only as examples of a class of test procedures or where researchers have made modification to the standard test method in order to evaluate cable fire performance. Attempts have also been made by several researchers to use standard test methods in novel ways to extract fire property data. Many of these standard test methods are described in detail elsewhere in this report. Also, different test procedures have been developed to extract some of the basic fire property data.

Many tests have been devised for the purpose of evaluating the fire performance of electrical wire and cable assemblies. Several have been introduced into industrial use as standard test methods. A general list of fire test methods can be divided into 10 categories:

1. Ease of ignition;
2. Flame spread;
3. Heat release rate;
4. Minimum oxygen requirement;
5. Smoke evolution;
6. Corrosivity;
7. Ease of extinguishment;
8. Toxic gas emissions;
9. Fire endurance;
10. Real scale tests.

The National Materials Advisory Board [119] has previously compiled a general list of fire test methods that included items 1 through 5 and items 7 through 10. Specific tests in each of the first eight categories are intended to determine a different material response under well defined exposure conditions. These measurements, however, do not necessarily represent fundamental material property measurements. Generally, the test results are affected by geometry of the sample (e.g., specimen size, thickness, surface orientation, etc.) and changes in the sample's environment (e.g., airflow, humidity, etc.). The selection of appropriate test methods is governed by a need to maximize specific fire attributes of a material. Specific fire attributes are chosen for maximization based on a set of exposure conditions defined by a probable fire scenario that could lead to ignition and fire growth. Given that the present set of available tests are single point exposures (i.e., evaluate fire performance under a unique set of conditions) with little hope of generalization, end-use conditions are ill-defined for most applications of these tests.

Fire endurance tests are normally designed to evaluate structural components with regard to their ability to retain fire barrier integrity and load carrying capacity. With the exception of cable penetration tests, these tests will not be reviewed in this report. Real scale tests are reviewed in another section of this report.

As will be obvious to anyone reading this report, over the years fire research has seen a proliferation of test procedures for the measurement of wire and cable flammability. **This is a direct result of the inability of current bench-scale test methods to measure fundamental fire properties that can be used to predict fire performance under a variety of fire conditions.** Every end user, such as Taylor [120], has been driven to specify an evaluation method based on preconceived ideas of the hazard associated with wire and cable flammability. This results in the inclusion of measurement parameters (i.e., falling materials, flaming droplets, etc.) that reflect this perceived set of hazards as related to a given cable installation.

5.1 Ease of Ignition

The ignition of a product is the first stage in the development of a fire. The ease with which a product ignites when exposed to a source of thermal energy typically encountered in end-use conditions may determine the suitability of a product for a stated application. Several test procedures have been developed to measure the ease of ignition of wire and cable assemblies. Most of these procedures determine ease of ignition as an additional measurement parameter to a measure of flame spread or smoke evolution. Therefore, ignition delay times are reported for tests conducted in the various calorimeters, and flame spread devices.

For example, Moulen and Grubits [121] investigated the fire behavior of multiple lengths of cables using a modified Australian standard originally intended for room wall linings (AS 1530.3-1982). The test was originally intended to simulate corner burning. Samples were prepared by placing parallel lengths of cables (450 mm long) on a noncombustible board. The assembly was mounted vertically opposite a radiant panel. A flaming pilot ignitor was used. During the test procedure, a sample is moved in steps towards the heater over a period of 20 min until ignition and flame spread occurs on the sample surface. The ease of ignition is described as the irradiance level that caused ignition in this apparatus.

Alvares, et al. [122] used an NBS ease-of-ignition apparatus designed to measure ignition time from a flame contact exposure. They determined ignition delay by measuring; temperature rise, thermal radiation rise, time to sustained flame attachment, and a visual interpretation of flame attachment.

5.2 Flame Spread

Flame spread tests, which measure the rate of flame propagation or the extent of burning, are designed to characterize products to the extent they could contribute to the growth of a fire. Some of these tests also incorporate circuit integrity requirements during or after the fire exposure. Any flame spread test presupposes the existence of a fire. The size of the ignition source used in these tests is an indication of which stage in a fire's development the test is measuring product performance. In general, small scale flame spread tests measure wire and cable fire performance at an early stage of fire development and are limited to a measure of the extent of fire damage from a given exposure. As will be seen, tests based on ASTM E 84 [123] measure fire performance later in the fire growth curve, but are still limited to

measuring the extent of flame damage or spread. Newer tests like the LIFT⁷ [124] are based on a different philosophy of fire measurement science. These tests attempt to measure an intrinsic fire characteristic of a product that can then be used to predict the extent and rate of fire damage or spread under a broad range of fire conditions.

5.2.1 Single Cable Tests

As seen in a previous section, numerous standard test methods exist for wire and cable acceptance testing for various end uses based on an evaluation of the fire performance of a single wire or cable assembly. For example, single cable tests such as MSHA 18.64 [125], ASTM D 470 [126], and portions of UL 44 [127] and JIS C 3005 [128] expose a small section of cable in a horizontal orientation to a bunsen type burner for a predetermined time period. Either a flame spread rate or distance is determined or the time to self-extinguish is measured. UL 83 [129], BSI 4066 [130], BSI 6977 [131] and portions of UL 44 use a vertical configuration and a bunsen type burner to evaluate single cables. The table below summarizes some of the test conditions. UL 44 has been used extensively [132] to measure the extent of flaming on single lengths of cable.

Hasegawa, et al. [133] modified the ASTM E-162 apparatus to assess the upward flame spread along an electrical cable using a variant of the flame spread model developed by Quintiere. They install a water cooled shutter between the gas fired panel and a vertical hung sample composed of a 46 cm length of cable. The cable samples were exposed to an externally applied irradiance of from 5 to 25 kW/m². They also installed two thermocouples: one on the jacket surface; one through the jacket on the conductor surface. The pilot burner was applied to the cable when the surface mounted thermocouple reached 100 °C. They evaluated the fire performance of seven cables (i.e., PVC, Polyethylene, Rubber, Neoprene, Hypalon) and calculated the Quintiere correlation parameters. At an external irradiance of 25 kW/m², the flame spread rate varied from 0.4 cm/s for the Hypalon to 2.6 cm/s for the rubber jacketed cable. Minimum ignition irradiance ranged from 28 to 33 kW/m². Fire constants theta and C varied from 0.68 to 1.5 and 1.1 to 2.0 (s/cm)^{1/2}(cm²/W).

5.2.2 Multiple Cable Tests

Extensive use has been made of the ASTM E-84 to compare fire performance of grouped or bundled cables. Several researchers [132] reported on tests conducted on communication cables as well as power carrying cables.

Patel [134] developed a small scale version of the ASTM E-84 tunnel in an effort to more rapidly evaluate new cable designs when evaluated against the requirements of UL 910. He built a mini-tunnel that was 1/3 the size of the UL 910 tunnel. Flame spread distance was limited to 5 feet. Cable samples

⁷ This test is an example of a flame spread test which gives data directly suitable for fire modeling; it is not generally relevant to the testing of cable products, since it tests for flame propagation *against* the wind, rather than *with* the wind. All existing cable tray tests use a with-the-wind configuration, since most of the better grades of cables are resistant to any against-the-wind propagation. Only in Tirrill burner type of tests is there any concern about downward propagation, since some lesser quality thermoplastic wires can show downward propagation.

that were 9 1/2 ft long were placed in a cable rack that was 9 ft 8 in long by 5 1/4 in wide. Other aspects of the test: burner, flame length, etc., were the same as UL 910. He found that for cables that burned less than 5 ft the correlation between the mini-tunnel and UL 910 was good. However, for cables that burned more than 5 ft in the UL 910, no assessment could be made in the mini-tunnel.

Kaufman [135] discusses the development of an AT&T and Bellcore horizontal cable tray test. The test uses a standard 5 ft cable rack, which is filled with cable to a depth of 2 in. A standard IEEE 383 burner is placed 10 in. below the rack and a 4 ft by 6 ft calcium silicate panel is centered 1 ft above the cables. The burner is set to the IEEE 383 energy level and applied to the underside of the cables for 1 hr. Extent of flaming is limited to an area that is only 6 in greater than the original flame impingement area.

Alvares, et al. [121], analyzed the fire performance of hypalon and rubber insulated cables using a vertical cable tray similar to IEEE 383. The samples were 1.8 m long and arranged in two layers. A burner was located at the lowest point of the vertical cable tray and adjusted to produce an incident irradiance of 50 kW/m² on the target cable.

Klevan, et al. [136] analyzed five test procedures with an eye towards the applicability of these test procedures to detect unacceptable fire performance in a nuclear power plant environment. The tests reviewed by them included IEEE 383, UL 83, the Baltimore Gas and Electric Company Test, the Philadelphia Electric Company Test, and the Consolidated Edison Company of New York 'Bon Fire' Test. The last three of these tests attempted to simulate the fire environment, as perceived by the test developers, one might find in a nuclear power plant with: multiple cables of varying size placed in a cable tray; ignition sources varying from a gas burner to a pool of transformer oil; horizontal and vertical cable orientations. Because of shortcomings in the duration of exposure, the size of the ignition source, and the size of the test enclosure, they felt that these tests would generally overestimate cable fire performance.

The European Space Agency [137] conducts several extent of flame spread tests on wire and cables intended for use in spacecraft construction. One test employs a test chamber of approximately 125 L in volume. A wire bundle composed of seven wires is laced together with non-flammable tape and placed vertically in the test chamber. Six wires are 25 cm long and one is 27 cm long. Electrical power (10% above the fusion current for the wire under test) is applied to the longest cable. The extent of burning on the wire bundle is measured. In a similar way, downward propagation is also assessed.

Grayson and Kumar [138] describe a bundled cable evaluation procedure used by the Italians (CEI-20-22) and the European Community (IEC 332 Part 3) that is based on a British Central Electricity Generating Board (CEGB) specification (GDCE21). This method utilizes a vertical cable tray mounted on one wall of 4 × 2 × 1 m compartment. The cable tray stands 0.15 m from the wall. Air flows into the chamber from the floor and is exhausted through a slot located above the cable tray. Tests are conducted with a gas burner set at 27 kW for 30 min. Extent of flame damage is the measurement criteria.

Mikado and Akita [139], [140] developed a moving wire method to measure flame spread rates on cables. The method uses a vertical tube furnace (6 cm diameter by 40 cm long) through which is drawn a cable such that the flame front is fixed relative to the exit section of the furnace. Measuring flame spread rate of grouped PVC cables in a range of oxygen concentration (21-70%), they found that the flame spread rate under preheating conditions of 220 to 260 °C were the same as a single cable preheated under the same conditions. At oxygen concentrations below 40% non-preheated grouped cables

had a higher flame spread rate than preheated single cables. As a side note, they also tested chloroprene cables at room temperature and found that the flame spread rate was unchanged as the number of cables was increased from one to three. They found that the flame spread rate could be fitted to the following correlation:

$$V = \alpha(T_p - T_a)^{-b} Y_0^n \quad (3)$$

where α is a coefficient which is a function of shape and thermal properties, T_p is the pyrolysis temperature, T_a is the initial specimen temperature, Y_0 is the oxygen concentration, and n is an empirically determined constant while

- b = 1 for thermally thin, and
- b = 2 for thermally thick.

Moulen and Grubits [120] used a modified Australian standard method (AS 1530.3-1982) to evaluate the flame spread time (i.e., the time a radiometer required to increase by 1.4 kW/m² above background) of multiple lengths of cable and the heat-evolved over a 2 min period after ignition as measured by a radiometer. They attempted to show a correlation between the flame spread time and the heat-evolved with the combustible cable volume per unit area.

5.3 Heat Release Rate

In this section, general studies on HRR of wires or cables are reviewed in the context of the various property measurement methods being examined. Because of the importance of this property, however, a later chapter of this report is devoted specifically to HRR techniques.

Research on the measurement of the heat release rate of materials and products has been ongoing for about 20 years. Recent developments in the measurement process has resulted in the availability of equipment to characterize the heat release rate of burning products. NIST (formerly NBS) developed several experimental heat release rate apparatuses in the early 1970's. One of the first and most widely used apparatus of the late 1970's was the Ohio State University Heat (OSU) Release Rate Apparatus [141]. This device measured the energy release rate of a burning product exposed to a control radiant source. By adding smoke analysis equipment to the exhaust duct, the apparatus could simultaneously measure smoke generation. In the late 1980's, another apparatus was developed by Babrauskas [142] to measure heat release rate based on the principle of oxygen consumption. This was called the Cone Calorimeter because of the shape of the radiant heater. Both of these heat release rate calorimeters have been adopted by ASTM.

Pocock [143] used the OSU apparatus to evaluate the fire performance of several electrical cables. His objective was to develop a correlation between the OSU apparatus and the IEEE-383 flame propagation test (this test is extensively discussed in another section of this report). During his investigations, Pocock also measured the effects of cable diameter, ratio of cross-sectional area of copper conductor to overall cross-sectional area of cable, cable spacing, and incident energy level on the burning characteristics of selected cables. He found that incident energy and cable diameter had the greatest effect on heat release rate, while copper ratio and cable spacing had slight to no significant effect on test results. Correlation with IEEE-383 showed that cables passing IEEE-383 exhibited a near zero total heat released

per square meter of cable surface during the first 5 min of the test. Cables that failed the IEEE-383 test exhibited total heat released during the first 5 min of the test that were substantially above zero.

Woollerton [144] used an OSU apparatus to measure the heat release rate from a set of electrical communications cables. The cables were mounted vertically, parallel to the heating elements. Based on this work and the work of Gouldson, et al. he was able to develop a model that could predict the fire performance of electrical cables in the Steiner Tunnel test. In a separate work, Smith and Woollerton [145] demonstrated that a fire model, based on the OSU results over a incident energy range of 15 to 60 kW/m², could be used to predict grouped cable fire performance as measured by IEEE-383. They conducted an interlaboratory evaluation of the model by comparing the results from the model using five cables and five laboratories. The results showed that the model predicted IEEE-383 results to within the scatter of the data from the interlaboratory participants.

Dube [146] used an OSU apparatus to evaluate six fire retardant coatings intended for wire and cable applications. Tests were conducted at 10, 20, 30, and 40 kW/m². He found that using IEEE 383 approved cables, coatings could be used to reduce the total heat released over the first 10 min. by 50% to 90% and 20% to 90% at 15 min. depending on specific coating. Alvares, et al. [121], also used the OSU apparatus to evaluate PVC and Neoprene insulated cables. At exposure levels of 27, 54, and 80 kW/m², they found that at 80 kW/m² the PVC insulated cables had a high heat release rate, 205 kW/m², compared to the Neoprene, 63 kW/m².

While not presenting any data on wire and cable performance, Vandeveld [147] discussed the use of heat release criteria in a reaction-to-fire test method. The method consisted of an insulated box with a volume of 0.7 m³. Ducts were provided for the inflow of air and outflow of combustion products. Cable samples, 0.3 m long, were attached to a frame. Cables were hung vertically. The cable assembly was exposed to a nonuniform external irradiance produced by an electrically heated panel inclined away from the sample surface such that the irradiance varied from 60 kW/m² to 5 kW/m². A pilot flame was used to ignite the sample at the high irradiance end of the field.

More recently, Braun and Shields [148] used the Cone Calorimeter to evaluate the fire performance of cables intended for naval applications. They found that a crude assessment could be made based solely on the peak heat release rate and the surface area occupied by a single layer of cables in an enclosure.

Tewarson [149] [150], at FMRC, has conducted an extensive amount of work during the development of the FMRC test method for the evaluation of the fire performance of wire and cables. The method is extensively reviewed in section 1.9 of this report. He and his coworkers developed small, intermediate, and large scale combustibility apparatuses for the purpose of evaluating cable fire performance.

5.4 Minimum Oxygen Requirement

ASTM D 2863 [151] is the prototypical design for an apparatus that measures the minimum concentration of oxygen, in a flowing mixture of O₂/N₂, necessary to support downward flaming combustion on a material supported in the flow stream. Oxygen Index (OI), or limiting oxygen index (LOI) values can range from approximately 14 to 70. A large OI number represents a material that is more difficult burn under standard atmospheric conditions. An old Bell System Protocol [152]

required that all materials used in electrical applications, including cables, must exhibit a minimum oxygen index of 28. Examples can be found that show polyvinyl chloride, sometimes used as a cable outer jacket, with an OI of 28 [153].

The European Space Agency [137] uses ASTM D 2863 as a screening tool for materials intended for space craft use. They require that materials not support combustion when tested at 10% higher than the expected O₂ concentration. Redfern and Treberne [154] describe application of ASTM D 2863 to telecommunications and power cables. They state that British postal authorities, using this test method, have required that materials must have at least an OI of 27 before allowing their use.

Keogh [132] used an oxygen index apparatus to classify the flammability of wire and cable assemblies. He found that as long as one compared within a family of polymers and assemblies, the test method could provide a good indicator of a materials flammability. Comparing results across a broad range of polymers produced inconsistent results.

5.5 Smoke Evolution

Guyot, et al. [155] developed a laboratory apparatus to measure smoke evolution of burning cables. The apparatus formed the bases of the French standard AFNOR T 51073. Small pieces of wire (100 mg) are placed into a tube furnace heated to 450 °C for smoldering conditions and 700 °C for flaming conditions. Air passed through the furnace at 80 l/hr. Measurements are made of the optical density of the smoke and the concentrations of CO and CO₂.

Keogh [132] used the Arapahoe Smoke Chamber, which measures smoke gravimetrically and also yields a measure of the ash formed during burning, to test the smoke generating characteristics of some wire and cables. He found that the results from the Arapahoe Smoke Chamber produced a fair correlation to comparable tests conducted using the NBS Smoke Chamber.

Grayson and Kumar [91] reported on the '3 metre cube' method for assessing smoke emission characteristics of burning cables. This method uses a 3 metre cubical room (a total volume of 27 m³). A section of cable is mounted horizontally over a 1 L alcohol burn, which will burn for about 25 min. A small fan is used to thoroughly mix the smoke. A light beam is used to measure smoke obscuration. An attenuation value, A₀ is defined as

$$A_0 = \frac{V}{L} \log \left(\frac{I_0}{I_t} \right) \quad (4)$$

where V is the chamber volume, L is the light path length, I₀ is the initial transmittance, T_t is the measured transmittance. British recommended values for A₀ are based on cable diameter such that:

Cable Diameter (mm)	Number of Cable Sections	A_o (m ⁻¹)
10-15	4	0.7
15-25	3	0.8
25-40	2	1.0
40+	1	1.5

5.6 Corrosivity

This is a new area of concern in fire science, not unlike combustion toxicity was in the mid-1970's. In 1986 DiNenno [156] prepared a background paper for ASTM E05, Fire Standards committee, on smoke corrosivity. He divided the smoke corrosivity problem into three areas:

- 1) Production of corrosive products;
- 2) transport of products;
- 3) response of exposed elements.

Most test methods attempt to reproducibly generate corrosive products of combustion, with the assumption that these products of combustion are produced in 'real fires.' Standard test materials are exposed to these products of combustion and a measure made of the corrosivity, usually by measuring a change in resistance in the test material. The problem of transport of corrosive products of combustion is not considered and most research work nor in assessing the hazard posed by cable insulating materials used in various installations. In this context DiNenno reviewed the works of Hirschler and Beitel on the transport decay of HCl. The work of Sandmann and Widmer on the corrosivity of PVC and fluoride containing smoke is also reviewed. DiNenno's major concern is that data from current test methods can not be used in hazard analysis. However, test methods could be developed that measure the corrosive potency of the products produced from the thermal decomposition of a material. This would be analogous to the concept of toxic potency of the products produced from the thermal decomposition of a material.

The current approach in studying smoke corrosivity is to decompose the product and expose 'coupons' of various specimens to the products of combustion (just like the toxicity tests where the rats are replaced by these coupons). Exemplary of these are two test methods which are currently being developed in separate ASTM subcommittees. Within subcommittee E05.21 a general-purpose method is being developed [157] which is to use a closed 200 L box, similar to the new radiant toxicity test apparatus. Within the Committee on Electrical and Electronic Insulating Materials, D09, there is active work in subcommittee D09.21 on a method specifically intended for use with wire and cable products. This test method [158],[159] uses the Cone Calorimeter to develop a combustion product gas stream that is passed through an 11.2 L exposure chamber. Within the exposure chamber, a target metal is exposed to the products of combustion and measurements are made of metal loss thickness of a target metal using a corrosimeter, which converts changes in resistance to metal loss thickness. Several investigators are currently collecting data using this test procedure.

Of older studies in the corrosivity area, a paper by Glew [160] reviews some of these better-known tests for corrosivity or acid gas emission. Ryan and co-workers have also reviewed some engineering aspects of corrosivity tests [161].

Grayson and Kumar [91] have described the operation of the French CNET test method to assess the corrosivity of decomposition products produced by burning polymeric products in a 20 m³ chamber. In the chamber along with the sample is a copper plated laminate. The test measures the change in the resistance across the laminate from a 1 hr exposure to the combustion products. An increase in resistance is a measure of the corrosivity of the combustion gases. Corrosivity is determined by

$$C = \frac{R_f - R_0}{R_f} \times 100 \quad (5)$$

Reported values are:

	C
PVC + PE (25% Cl)	24
PTFE	14
PE	0

Gibbons and Stevens [162] investigated the deterioration of electronic components when exposed to well defined acidic gas atmospheres. They conducted 22 hr exposures of 24 different circuit elements ranging from printed circuit boards to individual components such as transistors, resistors, and capacitors. Components were exposed to gaseous mixtures of SO₂, NO₂, HCl, HF, and CH₃COOH. They found threshold concentrations for these gases that produced visible and electrical effects within exposed components. In general electrical effects were noted at concentrations at or above 1000 ppm for all gases except for HCl, which had a threshold concentration of 100 ppm. This led to the development of a tests procedure that measured the emission characteristics of cable insulation materials in a bench scale apparatus. The apparatus consisted of a moveable tube furnace and a sample boat. Measurements are made of the gas concentrations produced during thermal decomposition at a controlled heating rate ranging from 1 °C/min to 100 °C/min in air, flowing at up to 1 Lpm, of the test material. pH and specific ion electrodes were used in the measurement process. This procedure forms the bases for CEGB specifications discussed elsewhere in this report.

At real scale, the US Navy has done a series of tests with Mil-Spec cables in a test ship in Alabama [162]. Hirschler has also surveyed some additional studies in the field [163].

Corrosivity is a newly emerging field which is in need of extensive research. The only information currently available is from limited testing, and is only indicative of the specific combinations of products tested (and under the conditions tested). In an attempt to limit corrosive effects, some have suggested banning of materials containing halogens. While this will eliminate corrosion from halogen-acid gases, these are not the only acid gases that can form; so corrosion may still occur.

It seems that we might learn from the similarity with toxicity. That is, if the susceptibility of products to corrosion or contamination by combustion products (gases or particulates) can be quantified, then the models which now assess toxic impact on people can be used to assess corrosive impact on products and equipment. But for now, the urge to adopt tests for corrosivity should be tempered with caution.

5.7 Ease of Extinguishment

One would think that the ease with which a burning product can be extinguished would be an important measure of the threat that the product represents to a fire protected occupancy. Despite the obvious relevance, no standard test method exists to quantitatively measure the 'ease of extinguishment' characteristics of a product. If 'ease of extinguishment' could actually be controlled, let alone measured, it might be possible to couple detection/suppression requirements to ease of extinguishment. This may allow for more flexibility in fire protection choices than are currently available.

5.8 Toxicity/Toxic Gas Production

While a great deal of research has taken place over the past decade on combustion toxicology, very little has been done specifically with wire and cable insulation products. This body of research has resulted in a wide selection of combustion toxicity test/screening methods [164] only a few have been applied to wire insulation. Notable among these is the reported, unusual toxicity of PTFE and FEP materials [165] later discovered to be observed only in the laboratory [166]. The following two studies are the only which were located in the present review.

Newman [167] conducted a laboratory evaluation for NEMA on five cable configurations. He measured HCl, smoke and mass loss rates from samples of non-metallic sheathed cable (12-2 w/ground) when tested in various types of conduits. The conduits included PVC, steel EMT, steel IMC, and rigid steel. Without providing any details, he exposed samples of cable and conduit to an external irradiance. He found that twice as much HCl was produced from PVC conduit and non-conduit tests than from the various steel conduit tests. He found that the HCl generation rate was dependent on the surface area of sample exposed to the external irradiance. Finally, more smoke was produced from the non-steel systems than the steel systems. Gouldson [168] reported on work using an analytical method that pyrolyzed small samples of PVC cable. He found that the HCl concentration of unprotected cables was expected to be less than 14% by weight.

Grayson and Kumar [91] describe a CEGB implementation of an NES 713 toxicity test for electric cables. Using a chamber with a volume of 1.0 m³, 100 g of polymeric product are placed above a bunsen burner. The product is decomposed by the burner and gas analysis is performed on the decomposition products to determine the concentration of a specific set of gases. A Toxic Index (TI) is calculated based on the sum of the ratios of measured gases to that concentration that is fatal at a 30 min exposure.

$$TI = \frac{Co_1}{Cf_1} + \frac{Co_2}{Cf_2} + \dots + \frac{Co_n}{Cf_n} \quad (6)$$

where Co is the measured gas concentration and Cf is the gas concentration that is fatal from a 30 min exposure.

It is important to note that these test methods/screens identify (1) a product's toxicity *relative* to other products on a per pound basis, (2) whether a product is unusually toxic or produces a unique physiological effect, or (3) whether a product produces an atmosphere toxic to some test animal under some conditions which may or may not be relevant to the context in which the product is found in the real world. What they *do not* determine is what difference this makes in terms of life loss or injury. Only

a fire hazard analysis can make this determination accounting for the major variables which affect the outcome of the specific fire scenario. Even more interesting is that nearly all of the data or results of these toxicity tests/screens are not useable as input data to the hazard analysis. For example using the HAZARD I fire hazard assessment methodology [169] one needs data on the yields of toxic gases as measured in the Cone Calorimeter (a HRR test, not a toxicity test) and the potential contribution of the product to death or injury from toxic gases is fully described. The only other information needed is a verification of the N-Gas assumption for the product by performing a screening test [170].

Several toxic potency tests currently exist, but have not specifically evaluated the toxic potency of combustible cable insulations. These include:

- NBS Toxicity Protocol [171];
- University of Pittsburgh Test [172] - this test forms the bases of the New York State toxicity testing requirements (although electrical cables have undoubtedly been tested, no data has been published in the technical literature);
- new procedure developed at NIST, based on Southwest Research Institute (SwRI) apparatus [173].

Each toxic potency test has a unique method for decomposing test products. Only the SwRI apparatus can be used to decompose wire and cable assemblies in configurations resembling real end-use conditions.

5.9 Fire Endurance (Cable ‘Poke-Thru’)

Cable penetration of a wall is necessary for moving power and information from one compartment to another. Numerous methods have been used for sealing penetrations in walls and floors. Although sealing with concrete appears to provide an excellent fire barrier, expansion of services and cable replacement becomes difficult and costly. Work has been conducted on alternate means of sealing ‘poke-thru’ holes around cables. The IEEE has developed a standard method for Cable Penetration Fire Stop Qualification Test [174]. The test method, IEEE 634-1978, is based on the ASTM E119 Methods of Fire Tests of Building Construction and Materials. This standard attempts to rate cable penetrations installed in rated barriers. Cable penetrations in the test are constructed with the intended barrier in the end-use configuration. Cable penetration fire stops are not acceptable if the specified temperature limits are exceeded on the unexposed side of the wall or ignition of the cable or fire stop products occurs. The presence of visible flame on the unexposed side within the fire rating time also constitutes a failure. Ratings are given in terms of hours (or fraction of hours) of endurance under a standard time-temperature exposure.

In an effort to develop acceptable penetration and sealing procedures that could meet IEEE requirements, several researchers have investigated the problem with emphasis on communications cables. While the reports generally described product development efforts, alternative evaluation methods were used because of the cost and time associated with standard fire endurance tests.

Quigg and Orals [175] performed fire tests on 10.2 cm (4 in) and 15.2 cm (6 in) thick floor slabs employing a standard fire endurance floor furnace. Using different hole and slot sizes, they evaluated different sealing methods. They found that a 1-hour floor rating could be obtained using a gypsum concrete and mineral fiber insulation combination or a Silicone, granular gypsum, and mineral fiber

insulation combination. Their primary concern was the development of sealing methods and, therefore, they did not investigate the interaction of sealing method and the design of cable assemblies.

McGuire [176], [177] found that a small scale test furnace could be used to evaluate various penetration schemes for a 15.2 cm (6 in) concrete wall. He found that sleeving cables with thin steel (26-gage) provided better resistance to heat transfer to the unexposed surface than a 5 cm (2 in), thick electrical conduit. He also looked at the effect of wire size and number of wire pairs on the performance of sealing products. For a 2 h exposure, it was noted that the fire performance of larger cables was not as good as the smaller cables. This was apparently due to the greater difficulty in packing sealing products around larger cables.

Kruczek and Cascio [178] investigated alternative design standards for cable vaults that would limit fire and smoke movement. The design standards were aimed primarily at new construction of telephone central offices. They designed a perforated block 'poke-thru' method that limited to one or two the number of cables in a specific hole. Sealing around one or two cables is easier and cable bundles, which are more susceptible to flame propagation are minimized.

An alternative to standard wall penetrations by cables was suggested and tested by Peverill [179]. His work involved the evaluation of electrical connectors installed in a firewall of an aircraft. The test method used was based on MIL-C-5015D, Military Specification for 'AN' type electrical connectors. The connector assemblies are mounted in a 1.6 mm (1/16 in) steel sheet and subjected to a flame positioned such that the flame temperature 6.4 mm (¼ in) from the assembly is 1,093 °C. The connector assembly is tested for current carrying capacity under combined thermal and vibrational stresses. He showed that a 20-min fire resistance connector: 1) could be developed with existing technology and 2) did not degrade the wall's fire stopping capabilities. More improvements in connector design would be necessary before this concept could be implemented in a broad range of applications.

6 Real-scale Testing

This section is a summary of available real-scale test data applicable to wire and cable products. To put these tests in context, a brief overview of the purpose and history of real-scale tests is provided. In the process, we see that although data are available in the literature, little would be of use in evaluating predictive models for assessing the hazard of these products.

From the earliest days of organized fire safety research, real-scale fire testing has played an integral role in advancing our understanding of fire behavior. For the present purposes, real-scale fire testing can be defined as studies of products and assemblies in sizes and configurations existing in actual end-use configurations. Within this definition, the discussion in this paper is limited to full size, single or multiple room fire tests. Real-scale fire testing of products and assemblies has distinct advantages over the plethora of bench-scale test methods available. Often, the smaller scale tests characterize only a few aspects of the products' fire performance under laboratory conditions without regard to the end use within a building [180]. Testing of the products in realistic scale and surroundings overcomes this limitation by affording an assessment of the overall fire behavior of the products as well as providing this evaluation in a realistic end-use setting. Recent attempts in predicting real-scale burning behavior of products from bench-scale test results have met with some success for items of furniture [181] and with less success for other, more generic products [182].

Testing in full size is not without disadvantages, however. Real-scale tests of room assemblies are often prohibitively expensive. A single test can cost from \$10,000 to \$50,000. In addition, the advantage of providing an overall assessment of the fire behavior of a product also can represent a disadvantage. By quantifying the outcome of the fire without a knowledge of the factors leading to the resulting fire and without relating the observed fire behavior to basic product properties, little insight into the intrinsic performance of the products may result. There is one additional but not very obvious tendency, in these cases, and that is to generalize the results. Given that real-scale tests are expensive, the tendency is to do as few as possible. It is far too easy then to make predictions well beyond the applicability of the results.

6.1 Early Developments

Prior to the mid-1970's there was not much need to make experimental studies of the details of room fires. Room fire experiments were typically conducted as an adjunct to studying fire endurance [183], [184]. For such purposes, it was necessary to track the average room temperature, since this temperature was viewed as the boundary condition determining what the wall, floor, column, etc., was exposed to. Neither the heat release rate, nor other aspects of the room fire such as gas production

rates were of major interest. While as early as 1950, some investigators, in conducting full-scale house burns, did try to study the gas production rates, as a means of determining how early untenable environments might exist [185], there was no great incentive to pursue the topic quantitatively. That incentive, in fact, came with the development of the mathematical theories of room fires. Post flashover room fire theories were being developed throughout the 1950's, 1960's, and 1970's. The more detailed understanding necessary for the pre-flashover portion of room fires was becoming achievable by around 1975.

During the 1970's empirical room fire tests were regularly being conducted at many fire research and testing facilities throughout the world. Instrumentation typically comprised a multiplicity of thermocouples; several probes where gas samples were extracted; smoke meters, typically located at several heights along an open burn room doorway; heat flux gages located in the walls of the burn room; and, possibly, a load platform. The load platform might register the weight of a single burning item, but was of little use when fully-furnished rooms were tested. Despite the fundamental role of heat release rate in the room fire, there was no technique available to measure that. Since neither the burning item's mass loss rate nor the air and gas flow rates could, in most instances, be determined, the measurements of gas and smoke concentrations at isolated measuring stations were not of much use in tracking evolution rates.

What may be difficult to comprehend in hindsight is that during the early 1970's the concept of measuring heat release rates in room fires was not appreciated. Today we view the heat release rate (i.e., enthalpy output) of a room fire as its single most important characteristic. An appreciation of its importance is a very new phenomenon. Part of the reason comes from the fact that tools of adequate quality for measuring the heat release rates in room fires were not available at that time.

Even before the era of heat-release-rate focused studies could begin, there were several series of notably thorough room fire experiments; two were conducted at Factory Mutual Research Corporation, while a third one was at NBS (now NIST). The first series at FMRC [186], [187], [188] served as a basis for the Harvard Computer Fire Code as a prime example. Three replicate full-scale bedroom fire tests in which the fire grew from an ignition in the middle of a polyurethane mattress to flashover were studied in enough detail to define the fire as a series of loosely coupled events. As the component parts of the fire became better understood, a model of the entire fire growth process as a series of quantitative calculations was developed [189]. To make these tests most useful for a scientific study of fire, several hundred measurements of temperature, radiation level, gas composition, gas velocity, and weight loss were made. The mechanism of fire spread from the initial burning mattress to other room furnishings, estimates of the flow of the gases through room openings, and estimates of the energy balance of the system were all quantified. The largest distinction between these tests and earlier test series was the carefully defined purpose; to understand the underlying principles of fire growth to be able to predict the progress of a fire in a generic building. A second series of tests at FMRC [190] extended this work by reporting on a simpler test configuration — single slabs of polyurethane foam in the room, instead of fully-furnished bedrooms. A similarly fundamental series of experiments was also conducted at NBS by Quintiere and McCaffrey [191], who examined wood and polyurethane cribs burning in well-instrumented rooms.

Contemporary real-scale fire testing is used for a variety of purposes and in varying complexities:

- understanding the burning behavior of products in realistic end-use settings [192];

- correlating the fire hazards of products tested in bench-scale apparatuses to their full-scale burning behavior [193], [194];
- exploring the underlying phenomena in the growth of the fire (such as flame spread, heat release rate, smoke production, and combustion product generation) [195], [196]; and
- verifying the predictive capabilities of fire growth and spread models [197].

6.2 Types of Real-scale Tests of Wire and Cable Products

Like other real-scale fire test data, available data specific to wire and cable products are reasonably scarce. Again, the prohibitively expensive nature of the tests limits the amount of testing that can be done in real-scale. Recent test data (from about 1970 to the present) falls into several broad and sometimes overlapping categories:

- electrical cables in open cable trays (mostly, although not totally in power plants),
- cable fires on ships (again, typically in open cable trays),
- communication and telephone switching cables (barrier penetration tests and comparison to small-scale test results),
- cable fires in building riser ducts, and
- studies supporting hazard assessment of wire and cable products.

Of particular interest in the real-scale test data would be data that would be useful in assessing the accuracy of computational models for predicting fire hazard of wire and cable products. Comparisons of such predictions with experimental measurements serve two purposes: 1) to determine, within limits, the accuracy of the predictions for those quantities of interest to the users of the models (usually those extensive variables related to hazard), and 2) to highlight the strengths and weaknesses of the underlying algorithms in the models to guide future improvements in the models. Typical variables that are of interest include

- fire pyrolysis and heat release rate,
- room pressure,
- vent flow,
- gas temperature, and
- gas species concentration.

6.3 Open Cable Tray Tests

Several researchers have studied the burning behavior of electrical cables in open cable trays, both in buildings and on board ships. Eichhorn and Pickering [198] investigated the fire hazards of multi-conductor cables in vertical, open cable trays. In one series, a control room of an industrial plant was simulated in a cement block room approximately $3.7 \times 7 \times 3.4$ m. Four different UL Type TC cable constructions were tested. Although considerable data including smoke density, gas concentration, and gas temperature were presented, no indication of heat release rate or specimen pyrolysis rate were available. Both of these are key measurements to successful modeling of the fires. Tests with similar products were conducted in different building constructions [199], [200], [201] with large amounts of cable. Again, the primary emphasis was on smoke production and fire detection, with little emphasis on other measurements key to hazard modeling.

The U. S. Navy conducted a series of real-scale cable fire tests to compare the differences between different cable types [202],[162]. Comparisons included burning rate, smoke, toxic and corrosive gas production. Numerous temperature and gas concentration measurements were made throughout the tests in several levels of a typical naval ship. Again, pyrolysis rate or heat release rate of the burning specimens was not reported.

Numerous studies of cable tray fires in nuclear power plants were carried out in the late 1970's and early 1980's. Tests in different size rooms ($7 \times 3.6 \times 3.6$ m and $12 \times 12 \times 6$ m) were used to develop guidelines for the detection and extinguishment of fires in grouped cable tray installations within an electrical utility environment [203], [204], [205], [206]. Two series of detector tests were performed. The first series, run in an intermediate-sized enclosure, tested the response times of ionization and photoelectric smoke detectors for combustion of 0.2 m lengths of several electric cable types. A second series, run in the larger enclosure, measured detector response times for complete cable tray assemblies. In both test series, primary measurements were smoke, temperature, and velocity near the ceiling. Specimen pyrolysis rate and heat release rate are available. These tests would be of use for hazard studies concentrated on detection and suppression.

In extensive tests, researchers at Sandia National Laboratories have investigated many aspects for cable tray fires in nuclear power plants [207], [208], [209], [210], [211], [212], [213], [214], [215]. The program included testing separation distances between cable trays, the effects of fire retardant coatings and various types of barriers with the cable trays were exposed to electrically initiated and external exposure fires. Testing to determine the effectiveness of various suppression agents and methods for suppressing cable tray fires as well as seal penetration tests to evaluate cable penetrations at positive and negative pressures were also conducted. Instrumentation in some of these tests was extensive. Measurements of cable and room gas temperatures, pyrolysis rate within the cable trays, heat fluxes within the room, and room gas concentrations were made. These data, if available in computer readable form, should be valuable for future comparison with model predictions.

6.4 Communication and Telephone Switching Cables

Real-scale experiments have been conducted with telephone cables in tunnels. In one series, an actual fire in a cable tunnel was recreated [216]. The cables used for the experiments had polyethylene sheathing and were of the same specification and layout as those in the real fire. Temperature, gas concentration, smoke concentration, and velocity were recorded along with electrical continuity in the cables. The main conclusion of the study — compartmentation of tunnels by fire resisting doors is an effective method to retard fire development is similar to an earlier study [217]. Again, lack of information on fire growth — pyrolysis rate or heat release rate — limits the usefulness of these data.

6.5 Cables in Building Riser Ducts

Development of test methods for listing classification for vertical fire spread [218], [219] included real-scale fire tests of 6 m long bundles of conduit and wire in a 0.25 m square riser duct. Products of combustion were vented into a third floor room where measurements of gas toxicity were made. Real-scale test results were then correlated with those from small-scale tests. Although useful in the development of the particular test method, they would be of use in predictive modeling only by providing pyrolysis rates for the cable types studied.

6.6 Studies Supporting Hazard Assessment of Wire and Cable Products

To address concerns over the toxicity of combustion gases from electrical non-metallic tubing, researchers developed a procedure for the assessment of the contribution of the product to the resulting hazard [220], [221]. Real-scale fire tests provided a level of validation for the method. A series of five tests were run in a $2.4 \times 3.6 \times 2.4$ m room connected to a 13 m corridor. They provide heat release rate measurement along with gas temperature and concentration throughout the space. These data have already been applied in the validation of predictive models with successful results.

7 Factors Governing Test Behavior

In this chapter we examine the effects of several ‘external’ variables on fire performance. By external we mean any variable other than the composition and construction of the individual cable. Such variables which can influence fire test performance are nearly limitless. They include various aspects of layout, orientation, packing density, tie-downs, etc. They also include such effects as wind speed, location (in the open or close to walls), ignition source strength, other details of the ignition source, and many more. Most of these have not been examined, let alone having been successfully incorporated into engineering calculation methods. Thus, we will only examine those few for which some data exist.

7.1 Ignition Source Strength

The issue of source strength, the power output of the source, is one of the most important questions in the fire testing of electric wires and cables, or any product for that matter. We will first consider the general engineering status of this subject, then examine the specifics for wire and cable.

We first make the observation that the current engineering emphasis on the power output of the ignition source is a relatively new concern. Traditionally, tests using solid or liquid ignition sources did not provide any estimate whatsoever of the power output of the source. Even when gas burners were specified, the primary specification was often a thermocouple reading at a certain location, the height of the inner blue cone, or a pressure reading at a certain point in the gas train. Only occasionally was the actual flow rate of gas even clearly described. This situation was largely changed due to the efforts of Rexford Wilson, a U.S. consulting fire engineer. For a period of several years starting in 1973 he conducted a campaign to measure the power output of common ignition sources and to get engineers accustomed to the concept of a single, quantitative scale for describing ignition strength. Thus, in this study as in any other modern work, we describe sources primarily by their power output and not by such concepts as ‘a 30 lb wood crib,’ which are still, unfortunately, occasionally found in use.

In general, changing the ignition source strength can change test results in three different ways:

- (1) The results (away from the source) are unchanged. If the test criterion is flame spread distance, peak heat release rate, or other variables measured far away from the source, it can happen that changing the source size has no significant effect.
- (2) The results are proportional (although not necessarily linearly) to the power output of the ignition source.
- (3) The results may show strong differences in propagating vs. non-propagating behavior. By propagating, we mean fires which spread away from the ignition source, extending nearly the full extent of the specimen. Non-propagating fires burn only in a limited region around the ignition source and do not spread further. By increasing the power output of the ignition source some

specimens may change their behavior only slightly; others, however, which showed non-propagating behavior with the smaller source may now show propagating behavior with the larger source. Thus, the recorded increase in fire hazard may be tremendous.

The latter point is poignantly focused in a U.S. Navy study [19]; DeLucia points out there *“Since most electrical shipboard cables are designed and certified to be ‘non-propagating’ and ‘self-extinguishing’ there appears to be a conflict between certification procedures and the real life shipboard fire conditions.”* Dube observes the same thing [222]—fire propagation from one tray to the next is possible, even for IEEE 383 qualified cables.

While the above summary is, we believe, technically sound and comprehensive, it is surprising how few good data exist to make clear these relationships. That is, the above statements are a function of our professional judgment and observation of numerous tests. They are not a simple textbook relationship which has been documented in well-controlled studies. We will now consider some of the known technical details of ignition, first for small specimens, then for large ones.

7.1.1 Ignition of Small Specimens

The ignitability of small solid objects is a surprisingly complex problem. The term ‘small specimen’ means one which is not much wider than the ignition source. For ignition sources, the discussion will only consider actual flames. Test methods using uniform radiant fields for ignition may be small in actual size, even smaller than the radiant heater. For reasons to be made obvious shortly, however, their behavior can best be studied by the same principles as are large specimens.

One difficulty with small specimen ignition is the 3-dimensional nature of the ignition process. A specimen which is roughly the same size as the nearby flame cannot be analyzed by means of 1-dimensional heat transfer theory, since there are usually sharp temperature gradients in all 3 directions. While mathematical computation of 3-D heat flow is certainly feasible, nonetheless setting up such computational problems is very tedious. Worse yet, the results, because of the numerous geometric variables, do not have enough generality to be reduced to simple formulas, nomographs, etc. Thus the problem has hardly ever been analyzed in the literature as such; we only know of one such study [223].

Another issue with small-specimen ignition is the area of thermophysical effects. When such a small specimen shrinks, flows, thermally deforms, chars, intumesces, etc., it can significantly change the critical distances between the flame combustion zone and its own surfaces. This becomes almost impossible to represent mathematically; we know of no success stories in this area.

Another problem is the effect of fire retardants. Products treated with FR agents often tend to show very good behavior in the small specimen/small flame situation. Performance may not be as good for the large specimen/large flame geometry. The reason for this can be visualized conceptually in the following simplified manner. Many fire retardants are formulated to volatilize readily and to do so at a temperature significantly lower than the surface temperature of a burning region. Thus, we can imagine a parallelepiped being subjected to heating only on the front face, but with FR agents being successfully volatilized out of the two adjoining sides. These FR agents act to quench the spread of fire on the specimen. There is now a ratio of three surfaces contributing FR agents, but only one surface actually

burning and needing to be quenched by these FR agents. Compare this to the situation where the heat flux is the same, but the specimen face is very large and so is the size of the heater (that is, the front face is uniformly heated, while the side faces are infinitely far away). The front face now has no 'help' from FR agents being volatilized from the sides. Thus the FR treatment will not necessarily be as good. This 3-dimensional nature of FR action would be difficult to model mathematically and, again, has not been attempted. The point is that this effect is related to the absolute as well as the relative sizes of the flame and source and object to be ignited.

7.1.2 Ignition of Large Specimens

A 'large' specimen can be defined as being large enough so that what is happening at the periphery no longer affects the results. This brings up an interesting dichotomy. A 100 mm by 100 mm specimen, such as used in the Cone Calorimeter [224],[225], can be considered a large specimen. There are two requirements for this: (1) the heating must be uniform over the entire area exposed; and (2) no phenomena occurring at the periphery, or along the edges should influence the results. Requirement #1 cannot be met with flame sources, but is readily met with the conical radiant heater. Requirement #2 cannot be perfectly met, but can be met surprisingly well. It requires that the heat source not heat the edges, and that the edges be protected from pyrolysis and combustion; further details are discussed in connection with some recent experimental studies at NIST [226].

VARIABLES TO CONSIDER

The heat transfer from a flaming source will depend on numerous parameters. The most important ones include:

- fuel type (gas, liquid, solid; of various chemical compositions)
- heat output of the source
- the direction of the flow of flames (parallel to the target surface, or perpendicular [this is generally termed 'impinging,'] or at various angles)
- distance from source to target
- type of oxidant (typically air, occasionally pure oxygen, as in an oxy-acetylene torch).

While these variables have all been studied in fundamental fluid mechanics or combustion science investigations, practical engineering advice to the fire test designer is scant. We start by observing one very useful generalization. For ignition sources where the fuel is gaseous, the oxidant is air, and the orientation of the burner is parallel and immediately adjacent to the target, a data compilation was made. A few years ago, a study at NIST examined various ignition sources, ranging from the very small to quite large [193]. It was found that, as the power output increased, the peak heat flux generally did **not** increase. Instead, only the area covered by the peak heat flux progressively increased. For flames ranging from an 0.3 kW Bunsen-type burner to a 50 kW wastebasket, the peak fluxes were remarkably constant at 30 - 40 kW/m². Quintiere examined another set of experimental data and found a range of 20 - 50 kW/m² [227]. Similar conclusions can be seen from the compilation of Paul and Christian [228].

Significantly higher heat fluxes can be expected when impinging flows are considered. For premixed, turbulent methane/air burners, for example, impingement region heat fluxes in the vicinity of 200 - 400 kW/m² can be found [229],[230]. These are values corresponding to the hottest zone and for gas mixtures which are fairly close to stoichiometric. Moving the target away from the hot zone, or increasing dilution of the combustion stream will, of course, show progressively lower heat fluxes.

For methane/oxygen or propane/oxygen flames, the heat flux values can be nearly another order of magnitude higher, with heat fluxes around 2500 kW/m² being found experimentally [231]. The above references also give more fundamentally calculational procedures. These, however, may not be easy for the fire test designer to apply. The difficulty is that such predictive methods require knowing an appropriate flame zone temperature, to be used in the computational expressions. Such temperatures are generally not readily available for arbitrary burners. You [232] has attempted to provide some scaling relationships for describing the fall-off in flux as radial or axial distances increase between the burner exit and the measuring point. These can give some guidance, but must be used with care, since they were developed using only very small fire sources and not verified against larger ones.

For such high heat fluxes to be observed, air velocities have to be substantial. This would not be consistent with the cable fire environment, however. Actual air velocities in the vicinity of burning cable trays have been reported at 0.9 to 1.2 m·s⁻¹ [21]. Since velocities scale with heat output (although not linearly) and since a fire source should not dwarf the expected target fire, such high velocity conditions would be inappropriate for a test method. We do find some data from impinging-type sources that are practical for use in fire tests. For instance, a 'T-head' burner was developed for igniting upholstered furniture. It consists of a tube with numerous small holes, thus discharging at a significantly higher velocity than would be the case of a large open-top burner. Ohlemiller and Villa [233] measured heat fluxes as high as 70 kW/m² in the impinging region of this burner's flame. In a parallel study using several different configurations of impinging flames from multi-hole propane and butane burners [234] more typical fluxes of 50 kW/m² were seen. In another study on various commercial burners and plumber's blow torches, a maximum impinging-zone heat flux of 140 - 150 kW/m² was seen [235].

Systematic studies of gas burner ignition sources

One of the few systematic investigations of ignition sources was a study done at the Technical Research Centre of Finland. Ahonen and co-workers [236] used as the test environment the large-scale fire test room prescribed by ISO DIS 9705 [237]; for their experiments the room walls and ceiling were lined with 10 mm chipboard. They examined two ignition source variables: power output and burner face size. The burner face size was seen, in most cases, to be of relatively small effect. Three different power outputs⁸ were examined: 40, 160, and 300 kW. The primary fire performance variable examined was time to flashover of the room. All three burner output levels were sufficient to cause flashover from the test combustible. The times to flashover from the two higher outputs were only slightly different; the times to flashover from the lower two output levels, however were very different, being about 2 to 3 times longer with the 40 kW source than with the 160 kW. In all cases it appears that there was sufficient combustion to consume most of the test specimen present. While the size of the burner face had little

⁸ Here and in most other fire engineering studies, the power output is reported on the basis of the *net* heat of combustion, in contrast with the burner rating used by the cable industry, where the *gross* heat of combustion is (inappropriately) chosen.

effect on the particular tests being conducted, the investigators did observe a feature associated with changing face size (while keeping power output constant): The point of initial ignition of the test wall was much higher above the face of the burner for the smaller face burners.

The above Finnish study did not examine the mapping of the heat fluxes from the burners to the adjacent test specimen. A more recent study from the same Finnish laboratory [238] gives results for gas burners of 40, 100, 160, 230, and 300 kW output levels, with the test burners having three different face sizes. From that study it is seen that for the more typical face sizes ($0.17\text{ m} \times 0.17\text{ m}$ to $0.30\text{ m} \times 0.30\text{ m}$) the peak heat flux recorded is dependent much more on the face size than on the burner output level. A peak value of around 40 kW/m^2 was seen with the smaller size and 65 to 80 kW/m^2 with the larger face size. For an unusually-large face size of $0.50\text{ m} \times 0.50\text{ m}$, the peak heat flux was seen to be strongly related to the burner output level; such a face size, however, is not used in normal fire testing. Published details are also available for a 50 kW burner [193] used at NIST in furniture testing. The main point to be observed about the burner fluxes is that (excluding burners with unusually large face dimensions) the peak fluxes are almost independent of burner output level, but the area behind the burner subjected to a given flux level is nearly linearly proportional to the burner output level.

Systematic studies of solid-fuel ignition sources

Very roughly, it can be estimated that the heat flux to *adjacent* objects from a small wood crib or other solid-fuel ignition source is in the same 30 to 40 kW/m^2 range as for gas burners. The picture is more complicated, however, for the heat flux from these sources to the object *underneath*. There are heat flux data measured from wood crib sources [239]. These measurements show small regions where heat fluxes in the vicinity of 90 kW/m^2 can be found underneath the burning crib. Unlike other sources, where we consider only radiative and convective heating from gases, in this case the high heat fluxes originate due to direct conductive heating from a hot, glowing body. Such high values are, in fact, consistent with the glowing char temperatures. The actual ignition process from such a source has not been characterized, however, since the heat transfer is definitely not 1-dimensional.

7.1.3 Electric Wire and Cable Studies

During the development of the IEEE 383 test, there was some controversy as to whether 21, 62 or 117 kW should be the proper burner power level. Soon after the IEEE 383 adoption, McIlveen [18] examined a single cable subjected to the 21 and the 62 kW levels. He found that the length of cable damaged was roughly proportional (2.7 times, instead of 3.0) to the burner output. He then considered that since simple 3x scaling holds, that contemplating use of the higher output source is not needed. Making such a generalization on the basis of testing a single specimen, however, could be considered unjustified.

J.J. Garland [21], of the Philadelphia Electric Co., observed that only tests run at the 62 kW level produce results which correspond to actual fire experience in their facilities. Data and details are not cited, however, so it is not possible to judge whether there has been a comparison between his experience and the results of such tests.

As discussed earlier, a UL investigation [26] focused on the proper burner power level to be used. Both improved differentiation between cables and improved repeatability of results were found at the higher 62 kW and 117 kW levels, compared to the standard 21 kW level.

Much later, in 1985, Stonkus [240] was investigating the stated lack of reproducibility in the IEEE 383 test and, in the course of that, compared some results for the same two values of burner output level. He examined three different cable types and two types of test ladders—solid and ventilated. His paper focuses on the important issue glossed over by McIlveen. Burner output level changes are, indeed, of little consequence when both levels evoke consistent flame spread results. What Stonkus experimentally observed, however, was something that is well-known in other areas of fire testing: a higher burner output can lead to very different product classification, since specimens where significant flame spread were not observed with the lower burner output led to fire conditions where the flame propagated to the very end of the ladder tray with the higher output level.

F.R. Postma conducted tests at three levels: 21, 62, and 117 kW [241]. His conclusions are similar to Stonkus' on the 21 and 62 kW levels—a number of cables are available which will not propagate fire at the 21 kW level, but readily do so at the 62 kW level. He concluded that the 117kW level creates a larger char length, but does not cause test failure on cables which would have otherwise passed at the 62 kW level. The general question of whether increasing the burner output level will cause cables to propagate that would not have propagated at some lower level, however, cannot be answered. This is clearly true for some cables and false for others. As an example of the latter, Barber and coworkers [92] did not find such transitions in the cables they studied at the 21, 41, and 62 kW levels. To determine the general relationship would require significantly more data than have been available to date.

Eventually, a cable tray test using a larger, 62 kW source was standardized in the form of the ICEA test, discussed above. Yet, the amount of comparative data published using this method is very small. A limited amount of such data are contained in the BFGoodrich study, discussed later in this report. The data reported are not sufficient to enable any firm statement on trends to be made.

The heat fluxes from the standard 21 kW burner used in IEEE 383 were characterized in a UL study [31], along with heat fluxes for the burner set at 10 and 31 kW. For the 21 and the 31 power outputs, the heat flux curves were very similar, starting at the impinging region at 39 kW/m² for the 21 kW burner and 43 kW/m² for the 31 kW burner, dropping to 20 kW/m² at 0.5 m above and down to 10 kW/m² at the 0.9 m mark. The 10 kW source produced a maximum of 35 kW/m² and dropped faster. These maximum values are remarkably consistent with the general ranges cited above for various ignition sources.

During their 1984 studies, UL also examined other details of burner specification, such as the air/fuel ratio to be used,⁹ optimal spacing away from the test specimen, etc. Since these investigations were mainly focused on standardization issues for the specific test burner and did not reveal generalized combustion findings, we will not review them in detail here.

⁹ The burner used in IEEE 383 and related tests is somewhat unusual in that it is a premixed burner. In fire testing, small sources, such as Tirrill burners, are normally premixed. Larger burners, such as used in room/corner testing, for example, are normally run as diffusion flames, without a premixed addition of any oxidant.

7.1.4 Location of Ignition Source

In the UL studies [31], one of the objectives was to verify if the standard distance (75 mm from the back of the cable tray) between the burner and the test specimen was appropriate. They found that there was an optimum spacing. For greater or lesser spacing, undesirable and unrealistic flaming conditions would occur. These included detachment away from the specimen surface, lifting of portions of the flame away from the surface, and deflection of the flame by the specimen back down onto the burner. At some spacings stability could be increased by changing the air/fuel ratio. The distance prescribed by the standard was seen to be satisfactory and no suggestion was needed for changing it.

7.2 Orientation

It is a well-known fact in fire physics that, all other factors being equal, fire will spread much more rapidly upwards than laterally (horizontally) [242]. Several studies are available on cable tray fires [26,108] where it has been documented that flame spreads farther in the vertical upward orientation than in the horizontal orientation. There is, however, not enough data on this point to be able to make quantitative predictions of the effect of orientation on the flame spread velocity or extent.

7.3 Packing Density

When cables are tested in trays, one of the most important factors to be considered is: What is the proper packing configuration? By configuration, we will generally refer to a simple packing density, where cables are placed in only one layer, and the distance is varied from one cable to the next. The IEEE 383 uses such a simple single-layer test arrangement and specifies that the cables have a clear spacing of 1/2 the cable diameter between each cable. In addition, the IEEE 383 method specifies that only the middle 15 cm (of a total 30 cm tray width) be filled with test specimens. Such an arrangement is very simplified. In real life, cables can be placed in multiple layers, be tied and bundled in groups, etc. Thus, there is a concern that any standard test should represent a 'worst plausible' packing density/configuration.

Stonkus [240] examined the packing configuration effects on cable assemblies where bundles of 3 cables were tested as groups. For three different PVC cables tested, he found that the IEEE 383 prescription led to the **least** severe test condition. The most severe was when the same spacing was used, but the whole tray width was filled, not just the center half. For greater packing yet (a solid packed one layer, or two solid layers) the severity again dropped off. The differences between the test conditions were most pronounced for non-FR specimens. Specimens of FR PVC showed substantially less variation between the packing conditions.

An initial UL study [27] found that there is an optimum packing density, expressed as a percent fill of the cable tray width. For the 21 kW burner this was determined to be 20%, as discussed under the IEEE 383 test, above. A subsequent UL study [31] also explored several different packing densities, but found that a few alternative packing prescriptions that they tried led to problems in repeatability; thus they did not recommend changes to this area of the standard.

A number of studies on this issue have been conducted by CEGB. They concluded that, for non-PVC cables, bundling is not especially significant in increasing fire hazard. For PVC cables of the late

1970's—early 1980's vintage, however, they developed the Critical Mass theory, as discussed in conjunction with the CEGB standards above. This theory has not been checked in other institutions, nor is there comparable experience with newer PVC formulations.

Several studies have also been conducted on this question in the IEC 332-3 cable tray test. Sydney-McCradden [108] summarizes the results of test programs carried out at BICC and at the Queen Mary College Fire & Materials Centre. The main conclusions were:

- Large bunches, *e.g.*, 16 or more cables, are less likely to propagate fire.
- Propagation of fire is less likely if the spaces between bunches are greater than 6 cm.
- Propagation of fire is less likely if the number of bunches does not exceed two.

In a related program, Barber and co-workers [92] showed some example data where cable damage for inter-cable gaps of 5 to 20 mm provided little difference in performance, but lowering or raising the gap distance outside of this range served to decrease the cable damage seen. Again, this has not been quantified with regards to the effects of cable composition or construction.

7.4 Size of Cable

Often the same basic construction is available in a range of cable sizes, varying from a few conductors to hundreds in one cable. Thus, it is of importance to know the effect that size makes on the results. From simple ignitability reasoning, one might surmise that thinner assemblies are more prone to flame spread than thick ones, since (within a certain range of thicknesses) the exposed surface will rise in temperature faster for the thinner sample. This was indeed the finding of Przybyla and co-workers in studying the UL 1666 test [48]. The same conclusion was found by FMRC, based on bench-scale ignitability testing [267]. The opposite result, however, was reported by Kaufman and Yocum for the UL 910 test [243]. The latter results, however, probably may not reflect actual fire experience. The Steiner Tunnel environment is significantly unusual in many of its features, and does not represent in a simple, analyzable way, fires in locales other than tunnels. Thus, lacking further data, it may be appropriate to assume that Przybyla's conclusion applies to most configurations, save that of the Steiner Tunnel.

7.5 Ventilation Rate

The IEEE 383 test specifies that the “test should be conducted in a naturally ventilated room or enclosure free from excessive drafts and spurious air currents.” This has proven to be very troublesome for test users, since even the basic choice of testing in a chamber or in an open room is left undefined. Most laboratories prefer testing in a chamber, however, for reasons of employee safety. Thus, the question of ventilation rate arises. Stonkus [240] examined two different air flows in a test chamber, 0.3 and 0.8 air changes per minute. For two different cables tested in 4 different packing arrangements, the above variation in air flow did not affect the results. Similar results were obtained in the UL study [31], where (cold air) exhaust rates between 566 and 849 L·s⁻¹ were examined. The observations of these two workers are also consistent with the finding of Parker in the Steiner tunnel, where varying the forced air flow

velocity over the range of 0.5 to 1.6 m·s⁻¹ did not affect the results [244]. This conclusion, however, is true only over a certain range of air flow speed. Studies conducted over wider ranges of speed show, instead, a shallow maximum occurring at a certain velocity. For instance, the study by Green and co-workers [245] shows that maximum specimen flame spread occurs at a wind speed of about 1.8 m·s⁻¹, with spread rates being slower for both lower and higher wind speeds. We caution the readers that the above numerical result is **not** a general statement, but should be taken as being pertinent only to the specimens tested by Green. Further support for their being an ‘optimum’ air flow velocity for inducing flame spread comes from a study by Kaufman and Yocum [45]. While their test objective was different and, again, not enough data were obtained for design guidance, they also saw greatest flame spread occurring at a certain air flow rate. Above and below this value, flame propagation dropped. This issue can be confusing, since other workers who examined a more limited range of wind speeds (*e.g.*, [246]) have reported a relationship of the form:

$$V_p \propto u_\infty^{1/2} \quad (7)$$

where V_p is the specimen’s flame spread rate and u_∞ is the wind speed. In view of more general findings, such as Green’s and Kaufman’s, we interpret this relationship to describe only low-wind-speed conditions; at higher values of u_∞ the flame spread will drop off instead of continuing to increase.

7.6 Other External Variables

7.6.1 Tray Type

Stonkus [240] examined the effect in the IEEE 383 of using the prescribed vertical ladder, versus a solid-back type of vertical tray. For four different cable types examined, the effect on flame spread was negligible for this variable.

7.6.2 Means of Anchoring the Cable

During the course of UL testing, it was observed that flame spread is increased when cable ties are non-metallic or are infrequent [31]. This effect, however, has not been quantified.

7.6.3 Room Configuration

It has long been recognized by fire protection engineers that there is a rank ordering in terms of fire severity:

- testing in the open, away from walls (least severe)
- fire against a wall (intermediate)
- fire in a corner, no ceiling (more severe)
- fire in a corner, with a close-by ceiling (most severe)

These relationships were originally studied by Thomas [247], but not in a way as to lead to quantitative recommendations. Later, some of these implications were also examined by Babrauskas [248]. There are still no general, quantitative recommendations; however, the recent study of Mowrer and Williamson [249] can offer some guidance. They conclude that “a fire in a corner is equivalent with respect to [room temperature rise] to a fire about twice as large in the center of the room.”

For electric cables, the only study on this topic that we find is one by Klamerus [250]. He conducted several tests in horizontal cable trays with various separation distances from a nearby wall/corner. He reduced his test data by examining weight lost as the critical determinant. For distances up to 1.8 m, he concluded that the weight lost was proportional to the inverse square power on the separation distance between the corner and the cable tray. For distances greater than 1.8 m there was no enhancement effect from the corner geometry. This relationship seems to ascribe a much more serious fire-enhancement effect than the one described by Mowrer.

7.6.4 Ambient Temperature

Stonkus examined the effect of changing ambient test temperature from 25 °C to 5 °C. For two different cable types examined under four different packing density conditions this variable was found to be negligible. In the UL studies on the IEEE 383 test, the temperature factor was also examined [28]. A significant dependence was not found over the temperature range that was studied. Additional data on the temperature effect are also available from Mikado and Akita [251]. They studied flame spread on a single wire in a special research apparatus where the wire was mechanically fed from a supply spool. While this configuration represents neither a common real-life scenario nor a standard test, the data are of some interest, nonetheless. In their study they found that the flame spread velocity is proportional to:

$$V_p \propto \frac{1}{(T_p - T_i)} \quad (8)$$

where T_p is the steady-state pyrolysis temperature of the wire (on the order of 350 - 400 °C for the PVC wires they examined), and T_i is the initial wire temperature. It is readily evident that, according to this expression, the initial temperature T_i would have to be changed to a value outside the normal range of ambient temperatures before any measurable effect on cable flame spread would be noted.

A more interesting question was raised by Lupton and co-workers [252], wondered if wires and cables should be tested at their maximum rated temperature, instead of at ambient room temperature. In support of their thesis, they offered the results of a number of *ad hoc* flame propagation tests. Not surprisingly, the results showed higher spread rates and greater damage when tested at the maximum rated temperature. Their view does not appear to have much support in the profession. Certainly it would appear to be excessive if applied to control cables, where reaching the maximum rated temperature would constitute an extremely unusual service condition.

7.6.5 Aging

Aging can affect polymers in three ways: (1) plasticizer and other volatile components will evaporate; (2) fire retardant agents change chemically, or evaporate; and (3) by changes in the base polymer itself.

General principles cannot tell us much more than this—for more quantitative guidance a study of a specific formulation would be needed.

The issue of aging of cables arose in the nuclear power industry. Sandia Laboratories conducted a series of empirical tests of two commercial cables commonly seen in nuclear power plants. The cables were subjected to an accelerated aging protocol. Specimens were then tested in a full-scale fire test facility and compared against the performance of un-aged specimens. The test rig provided for a 61 kW burner, but neither the burner nor the cable tray resembled the ones used in IEEE testing. A square sand burner was used. The cable tray configuration was arranged somewhat similarly to that in the Schlyter test [253]. Two cable trays were erected facing each other, separated by a small distance. Each cable tray was backed by inorganic millboard, to provide maximum confinement of the combustion products to the channel created in the middle. This test condition was much more severe than the one in IEEE 383. It was developed because the specimens to be tested *pass* the IEEE 383 test; thus, if a change in their fire characteristics is to be noted, a more severe exposure condition must be imposed. The results showed that the aged cables had reduced flammability.

7.7 Requirements for Circuit Integrity

A number of military standards, British standards, etc. were seen to include criteria on circuit integrity. This is a requirement which states that for a certain duration of time when exposed to fire (typically 20 to 30 min) circuit integrity must be sustained. The justification is, generally, that the provision is intended for cables used in emergency communications or control circuits, which must survive and be operational during a building fire. We may accept the premise that certain control or communications circuits must be assured of working during fire conditions. But, are such test requirements appropriate? They do not appear to be so. Building codes generally provide requirements for fire endurance of beam, columns, and other building members for up to 4 h. In the case of many noteworthy fires, however, such a requirement proves to be very optimistic. It is not at all uncommon for fires to take on the order of 24 h to control and extinguish. Thus, we conclude that such test, while well motivated, are inappropriate from the point of view of actual fire conditions.

In some cases, the avowed purpose of a circuit integrity requirement is to permit an orderly shutdown of a facility. Such a requirement, by contrast, can be reasonable, since the time period during which shutdown can be accomplished is rather modest and cables can be made which meet it.

8 HRR-based Cable Testing

In the majority of fire cases, the most crucial question that can be asked by the person responsible for fire protection is: ‘How big is the fire?’ Put in quantitative terms, this translates to: ‘What is the heat release rate (HRR) of this fire?’ Recently NIST examined the pivotal nature of heat release rate measurements in detail [254]. The reader should review the above reference to obtain the proper understanding for this section.

The heat release rate of interest is the one occurring during the actual fire. Later, we will consider how engineering tests involving less than a real-scale mockup can be used to give suitable guidance.

8.1 Measures of Fire Hazard

The reference cited above documents in some detail the fact that hazard to human occupants of buildings or other structures under fire is most directly related to heat release. We now need to consider some of the underlying concepts in more detail.

8.1.1 Occupants Intimate with the Fire

This category includes occupants whose clothing is on fire or those who are directly in contact with a flaming object. The injury potential for this category of occupant is mainly governed by the local heat transfer from the clothing or burning object to the skin. This is a specialized problem and, since this would rarely occur in connection with electric wiring, we will not pursue the topic here.

8.1.2 Occupants Remote from the Fire

In this case we consider occupants who are either in the room of fire origin, but not close to the fire, or who are in another room of the building. In earlier decades, the question of how to describe this hazard was a puzzling one for fire protection engineers. The traditional tests for the flammability of wire and cable focus on

- ignitability
- speed of flame travel
- maximum distance of flame travel or maximum length burned.

These were measures which were implemented largely because the technology was available for doing it. It was **not** done because a hazard analysis indicated that these variables are what correlated to incapacitation or lethality of humans.

The speed of flame travel (or extent of flame propagation) is **not** what injures persons in a fire, once we have accepted that they are not intimate with the fire and that clothing flammability is not the issue. Instead, injury comes from high temperatures, high heat fluxes, and large amounts of toxic gases being emitted. All of these injury-producing variables scale very closely with the heat release rate of the fire, but not solely with the speed of flame travel or the extent of flame propagation.

We now realize, as set forth in the above reference, that life threat to occupants (those not intimate with fire) is directly correlated to the HRR of the fire. We must emphasize that here we are speaking of the HRR of the **real-scale fire**. A real-scale fire may be the most valid test, but it rarely is a practical test; we desire to do testing on a bench-scale, instead. Bench-scale testing is cheaper and easier than large-scale, but there are also a number of potential technical advantages, if the test is designed correctly. These include:

- increased ease of obtaining repeatable and reproducible results
- the ability to measure more basic fire properties of the test specimen (something which is generally not captured in the large-scale test).

Reference [255] discusses a number of other aspects pertinent to the design of proper bench-scale reaction-to-fire tests. We now consider how to predict the HRR of the real-scale fire. In some situations, the real-scale HRR of the fire (kW) is directly and simply correlated to the bench-scale HRR. The bench-scale HRR, however, is measured on a small specimen of fixed face area and is reported as kW/m². Thus, in fact the correlation then goes schematically as

$$\dot{q}_{fs} = \dot{q}_{bs}'' \cdot A \quad (9)$$

where we have, for the moment, ignored the time-dependent aspect to the problem. The quantity A is the area of the full-scale specimen which is burning. For a simple, direct correlation to succeed, it is clear that either

$$A = \text{constant} \quad (10)$$

or

$$A \propto \dot{q}_{bs}'' \quad (11)$$

must hold true. In some cases, it does [255]. In others, however, a more detailed expression must be sought. In such cases the behavior of the burning area $A(t)$ must be accounted for as a function of time, based on appropriate test results in a bench-scale test. The general procedures for doing this have been worked out by Wickström and Göransson [256],[257]. Wickström and Göransson examined the case of combustible wall/ceiling linings in a room. This, of course, is not an electric cable application; the principles, however, are identical. A product covers certain surfaces; flame spreads over the product; the total heat released by all portions of this burning product is tallied up. The calculational procedure involves a convolution integral of the bench-scale HRR and an expression for $A(t)$. The latter is found to be a function of the ignition time, as measured in the Cone Calorimeter.

It is especially important to note that the fire hazard is **not** proportional to the flame spread rate or to the amount burned. These latter data have been published by Jianmin [258] for the same product where real-scale fire performance results are quoted by Wickström and Göransson. It can be seen that the Wickström/Göransson calculational procedure is necessary and is successful, while a simple direct examination of flame travel results does not at all assess the fire hazard.

8.1.3 Tests Needed

A *reference* large-scale test will always be needed for any product category. Bench-scale tests can then, if suitably validated against real-scale fires, be used to provide for most of the needed product testing. Thus, the large-scale test will rarely be needed in practice. But, it must be available for those situations where the bench-scale test is not applicable. Reference [255] gives further guidance on this point.

8.2 Bench-scale Studies

OSU studies

The first reported use of bench-scale HRR testing for cables was by Gouldson and co-workers in 1975 [259], who used the Ohio State University (ASTM E 906 [260]) apparatus. Shortly thereafter, they reported a second study [261] on this topic. In the second study, they added a circuit continuity test portion to the OSU testing. Based on current-day knowledge, this would not be considered advisable. Circuit continuity failure cannot be realistically assessed using bench-scale testing. Failure is both a thermostructural issue and is also associated to the way that cables are tied down and permitted or not permitted to deform under actual fire conditions. Such simulation cannot, as of this date, be done in bench-scale. The second part of their study was an attempt to mathematically model the conditions in the UL 910 test. All of the above exercises were purely hypothetical, since no comparison to, or validation against, any large-scale data was presented.

A number of HRR studies using the OSU apparatus were also conducted at the U.S. Navy David Taylor Research & Development Center [262]. One interesting finding was that, for the bench-scale specimens, the ratio of the copper volume to the total cable volume had only a slight effect on the HRR results. The study also examined performance in the IEEE 383 and a preliminary attempt was made to correlate the bench-scale HRR performance to that measured in the IEEE 383 test. The most successful test irradiance in the OSU apparatus for this purpose was found to be 20 kW/m². While bench-scale HRR testing was obviously the way to progress, the OSU apparatus used by these early investigators has some very serious limitations (*e.g.*, [263],[264]).

FMRC studies

The FMRC bench-scale HRR calorimeter was developed in 1975 [265]. Shortly thereafter FMRC started using it for the testing of electric cables. By 1979 a large amount of data was assembled and presented to EPRI [266]. These initial tests were run at a wide variety of irradiance values. The testing and interpretation of data were in agreement with standard engineering principles of HRR. By 1983, however, while still reporting generally standard data, FMRC began including some tests run in a 40% oxygen atmosphere [267]; tests both with and without enhanced oxygen were now being

conducted at an irradiance of 60 kW/m^2 . In this particular 1983 report, most cables were tested under normal oxygen conditions. Cables made from fluorinated polymers, however, since they did not readily burn at the 60 kW/m^2 irradiance in room air, were tested, instead, in a 40% oxygen stream. This could be considered highly peculiar, since normal engineering practice is to test all test specimens at identical test conditions, not to attempt to incinerate the better-performing specimens by exacerbated challenges. No mention is made in a 1984 summary of FMRC testing procedures of the elevated-oxygen situation [268].

By 1987, however, cables at FMRC were being tested at an irradiance of 50 kW/m^2 , but with oxygen levels of 30 to 45%¹⁰ [269]. Thus cables were now being tested 'impartially,' but all of them at an oxygen condition which is impossible in building fires. No reason was given why the 60 kW/m^2 irradiance was dropped to 50 kW/m^2 . Most significantly, the FMRC HRR calorimeter had been converted into an instrument which would no longer be termed a 'bench-scale HRR apparatus or calorimeter.' One of the hallmarks expected of a useable bench-scale HRR apparatus is that the irradiance imposed on the specimen be uniform across the face, or nearly so. Instead, the unit was converted into a small-scale scale model of a burning cable assembly. A single cable was stretched vertically through the apparatus, being heated by the nominal 50 kW/m^2 irradiance near its base, falling off to a very small value over 0.61 m height of the specimen.

FMRC deviated to developing their own test standard before reporting any validation results on their bench-scale HRR apparatus while it was still being run as a HRR apparatus. Interestingly enough, however, B.T. Lee, of NIST, examined some FMRC data and found that a potential correlation; this is discussed below.

LLNL studies

A series of HRR tests on electric cables was reported by Alvares and co-workers at Lawrence Livermore National Laboratory in 1982 [270]. The apparatus used was a larger-than-bench-scale heat release rate calorimeter built at Stanford Research Institute [271]. While quite large cable specimens (nearly 0.1 m^2) could be tested, the apparatus, nonetheless was configured to provide uniform irradiance over a section of a densely-packed cable layer, in the same way as it would in any normal bench-scale HRR test. Example results for some PVC and Neoprene cables were reported, but further studies were not carried forth.

Cone Calorimeter studies

Most of the recent bench-scale studies on electric cables have been done in the Cone Calorimeter. The first few studies focused on developing the needed measurement techniques and obtaining characteristic data for various cable types. Breazeale reported on a study describing proper specimen preparation and mounting techniques for cables [272]. Braun and co-workers examined the performance of a number of cable types manufactured according to U.S. military specifications [273]. O'Neill examined the data for a number of different polymer types used for cable manufacture and also compared the results to those from older bench-scale tests [274]. Matheson and co-workers also examined data various

¹⁰ It appears that only a range of O_2 values was given because it may have been difficult in the test procedure to control the value more closely; the report does not indicate a precise cause for this wide range of deviations.

types of polymers used in cables and compared results to several European tests, including the 3 m Cube smoke test [275]. Similarly, Coaker and co-workers examined results from the Cone Calorimeter and compared them to ones obtained from the OSU apparatus [276].

HRR Testing for Developmental Purposes

Determining the reaction-to-fire characteristics is usually an important aspect of the development of any new polymer formulations for wire and cable use. Under the present system of testing, for both traditional and HRR tests, this requires that a trial run of wire or cable actually be produced for testing purposes. Such a step can be costly and unrewarding if the formulation does not work out. It is significantly easier and cheaper to produce only test plaques of a new trial product. The question then becomes, Can a testing procedure be worked out where realistic HRR data are obtained from plaques? This issue has not yet been answered definitively. However, Pocock's finding that actual copper loading influences results only slightly is encouraging. A strategy should be pursued where HRR data from layered 'plaque composites' are compared to large-scale data on actual cables. Such layered composites should be made by incorporating plaques representing jacket material and wire insulation material in appropriate thicknesses. Copper conductors can be represented as a solid slab of copper, while metallic braids can be represented by flat sheets of braided metal.

8.3 Larger-scale Studies

In 1984, as part of its study for the NRC of the IEEE 383 test, UL installed HRR instrumentation on their IEEE 383 apparatus [31]. This study demonstrated the viability of including HRR measurements in the standard test; however, not enough data were obtained to derive a quantitative relationship between passing the test and an HRR limit value. Additional data were documented by UL in their UL 1685 test [50].

During recent years, Sandia Laboratories have installed large-scale HRR measurement facilities and have started reporting their cable testing results in HRR units (*e.g.*, [253]). The amount of data reported so far, however, is small.

Significantly more extensive new data were reported in two new testing programs, one at UL, the second at BFGoodrich; these are considered in Chapter 10.

9 Fire Performance of Wire and Cable Products

In the past, a number of efforts have been made to formulate a mathematical description of what is happening either in a large scale cable fire test or in a specific cable tray fire scenario. Here we will review the better-known of these efforts. This is a tough problem, but with a very high return once it has been solved.

9.1 The Johns Hopkins University Model

L.W. Hunter, of the Applied Physics Laboratory of Johns Hopkins University constructed a mathematical model of the burning of electric cables in horizontal cable trays [277]. The model considers several layers of horizontal cable trays, one above the other, and addresses the question of fireballs propagating from a lower layer to a higher one. The model was developed as an educational exercise. Since no provision was made for inserting actual bench-scale test results or physical property measurements of cables being studied, it does not appear to have been intended for engineering use. The model, while motivated by large scale testing at Sandia Laboratories, was not verified against actual experimental data.

9.2 The Clarke Model

In 1975 R.K. Clarke, of Sandia Laboratories, described a model he had developed for cable tray fires [278]. The model is somewhat similar to Hunter's in that it also tries to predict the effects of fire in a horizontally oriented lower tray on a cable tray above it. Additional computations are also made for leaping spread to horizontally adjacent cable trays. The model consists of a series of simple hand calculations on plume velocities, burning rates, and heat transfer. Clarke's calculations lead him to claim that vertical separations of 1.5 m and horizontal separations of 1 m are sufficient to prevent flame spread from leaping to adjacent cable trays. The model description is not accompanied by any results of measurements in either bench-scale or real-scale cable trays.

9.3 The OSU Model

In the late 1970's, Prof. E.E. Smith, of Ohio State University, G.R. Woollerton, of Northern Telecom Canada, and their co-workers proposed computational models for vertical cable ladders [279]. They attempted to model two vertical cable tray tests—the IEEE 383 and the Ontario Hydro test [71]. The main feature which has to be predicted for such tests is the extent of flame spread. The model used for flame spread was based on a very simplified ignition concept, not one consistent with current-day understanding of ignition and flame spread mechanisms (see, *e.g.*, [280]). The needed heat release rate data were obtained from the Ohio State University apparatus (ASTM E 906). The model also required that various thermophysical properties, such as decomposition temperature of the cable and effective flame temperature, be supplied by the user. It is not clear how the authors obtained these values. Results of a study on five cables were presented, but no engineering procedure was presented that appears usable by others. No subsequent work has been presented using this method.

10 Correlation Methods for Prediction

In the previous chapter we considered some theoretical attempts to model the behavior of cables in fires. So far, for various reasons, none of these methods is completely satisfactory. Yet, progress is being made. In this section we consider simpler, correlation-based approaches. We shall see that successes in such correlation-based approaches are already being reported. This will lay the ground work for more complete modeling, together with validation.

10.1 Methods Based on HRR Testing

Basis for the Need for HRR Testing

The majority of tests used by the cable industry today rely on either a ‘screwdriver’ measurement after the test to determine the burned length, or else observation during the test of the farthest extent of flame travel. These are criteria which are exceedingly difficult to standardize and to achieve reproducibility, since they are not direct measurements. Instead, both observational skills and personal interpretation play a very significant role in such assignments of length.

Further, neither the farthest extent of flame nor the length of cable damage are appropriate criteria of *fire hazard*. Ignitability of other objects (save violently flammable ones) requires significantly more heating than the very flame tip applied for an instant. Hazard to persons is also not measured by this variable. Similarly, extent of cable damage does not reveal at all adequately the costs which will be associated with restoring a facility to service.

10.1.1 Direct Correlation Approaches

Recently two studies have been completed where bench-scale data were obtained in the Cone Calorimeter, larger-scale data were obtained in the IEEE 383 or the CSA FT-4 rigs and a predictive correlation was derived between the two.

In at least two laboratories—UL and BFGoodrich—heat release rate measuring instrumentation has been installed in connection with the vertical cable tray test rig, allowing suitable intermediate-scale (although not real-scale) HRR measurements to be made. In the first part of the study conducted at UL [285] a correlation was obtained between the length of flame damage and the peak HRR. It was found that flame damage exceeds the maximum 2.4 m allowed when the peak HRR > 90 kW. Next, bench-scale Cone Calorimeter tests were made at irradiances of 20, 25, 30, and 40 kW/m². Based on preliminary data analysis, an irradiance of 30 kW/m² was seen to best predict the IEEE 383 test results. Specimens showing bench-scale HRR values greater than 200 kW/m² (at an irradiance of 30 kW/m²) were likely to exceed the 90 kW limit in the vertical tray test.

A more exhaustive set of specimens was examined in a similar series of tests where cone calorimeter tests were conducted at BFGoodrich while intermediate-scale tray tests were conducted, separately, at both UL

and at BFGoodrich [286],[287]. The vertical tray tests used were the UL 1581, the CSA FT-4, and the ICEA T-29-520. The Cone Calorimeter tests were conducted at irradiances of 20, 40, and 70 kW/m². Unlike in the UL study, the bench-scale data were used to predict directly the cable tray peak HRR. It was found that the results of the UL 1581 and the CSA FT-4 tests were best predicted by Cone Calorimeter tests run at an irradiance of 20 kW/m². The ICEA test, which uses a higher burner output, was somewhat better predicted by Cone Calorimeter data taken at an irradiance of 40 kW/m².

An additional variable explored in the BFGoodrich studies was the correlation of smoke results. A means of data analysis was developed which was able to predict the cable tray smoke results, based on Cone Calorimeter data.

It can be pointed out here that bench-scale test irradiances found useful in the above two studies were in the range of 20 to 40 kW/m². This is also consistent with the irradiances measured from typical expected ignition sources, as discussed above. This range is significantly lower than the 50 - 60 kW/m² used in the FMRC studies.

10.1.2 Methods Based on Separate Accounting for Flame Coverage Area

In 1985 B.T. Lee, of NIST examined some results from cable tray tests conducted at FMRC [288]. He correlated results obtained by Sumitra on large-scale tray tests [289] against tests conducted in the bench-scale FMRC apparatus, while it was still being run as a HRR apparatus [290]. The correlation was done in two steps. The increase in flame-covered area was correlated against the bench-scale HRR data; then, the cable tray HRR was predicted using a factor for HRR per unit area and a factor for flame-covered area. While not perfect, the correlation was seen to be promising. Part of the reason for the scatter which was seen might be attributable to the high irradiance of 60 kW/m² having been used in the bench-scale HRR tests.

10.2 Methods Based on Other Tests

In 1986 Hasegawa and co-workers at the Lawrence Livermore Laboratory described some developmental testing they had done to characterize flame spread behavior [291]. The bench-scale test method used was a novel modification of the ASTM E 162 flame spread test method. The E 162 method has not normally been used for cable testing, although such specimens can be readily accommodated in the test rig. In the standard E 162 test, a specimen is inclined 30° from the vertical and spreads flame downward. In the LLNL experiments, a vertical specimen holder was installed and upward flame spread was initiated. Analysis of the results was also not done in accordance with the standard E 162 formulas. Instead, the theory of Quintiere [292]—which describes *downward* and other against-the-wind types of flame spread—was used. The results were reported in the form of the various flame spread parameters in the Quintiere formulation. Since validation against appropriate full-scale fires was not reported, it is not possible to assess the fruitfulness of this approach.

However, these types of tests and predictive capabilities are interim measures. In the next section there is a discussion of a better way to quantify the hazard due to cables in fires. While the correlations are useful for making estimates, true evaluation of wire and cable as a hazard in a general scenario awaits the development of a full scale hazard model which includes the self-consistent pyrolysis/ignition/radiation-field.

11 Scenario Based Modeling of Fire Hazards

11.1 Background

The primary goal of fire safety regulation (after preventing the ignition) is to limit the impact of the fire on the building and its occupants. This has traditionally been addressed by placing a limit on the burning behavior of products in some standard test method which was intended to simulate a realistic threat. [For example, classical fire tests such as the ASTM E 84 [293] which evaluates the performance of interior finish products when exposed to a standard fire condition representative of a broad range of applications for these products.] We now know these test methods can be misleading when applied to products without proper regard to their context of use, such as the testing of low density plastics in the E-84. In many cases there is only a tenuous connection between the results of that test and the property that was being checked. This applies to toxicity, flame spread, and ease of ignition among others.

These concerns are elucidated earlier in this report under both the chapters dealing with standards (by country) and the supporting research. In general it is difficult to make the 'cross walk' necessary to substantiate the assertion that some critical property was measured. However, the advent of modeling, developed mostly over the past decade, is having a profound impact on our ability to evaluate realistically the fire hazards of materials and products in their actual context of use. A subsidiary benefit of these techniques is that it should be possible to predict the properties of products in the test configuration to understand exactly what was being measured, should there be an interest in pursuing the test apparatuses.

We no longer need to depend on the stand-alone methods for determining the degree of fire safety afforded by a product. We can now integrate the complex interactions of products with each other in the context of their application and use, interactions which are not considered in traditional test methods. We can determine how the deficiencies of one product are offset by the strengths of another, resulting in a safe combination. A good example of this is the use of blocking layers in aircraft seats [294] which protect the foam core for sufficient time to allow safe evacuation of the passengers. This allows us to retain the foam's benefits of comfort and light weight and still provide the necessary safety.

It is the newly-emerging science of predictive fire modeling that enables us to evaluate the combination of a product and the environment in which it is being used. Nowhere is this more important than in assessing smoke toxicity from the burning of concealed combustibles. Here, the surroundings of the product affect its burning behavior as well as the movement of the smoke to where people might be harmed. Of even more importance, the models allow one to keep track of the contribution of the product, relative to the smoke produced by other combustible items which may be involved. This is a breakthrough, since only the total smoke toxicity can be measured in tests.

Concurrently, this predictive capability has advanced the field of real-scale testing. Now one can obtain both supplementary and confirmatory information when these tests are conducted in a fully-integrated program with computational studies. This enables one to perform a thorough, previously-unavailable evaluation of wire and cable products currently found in the market. Wire and cable comprise a broad range of related products found in every occupancy. This includes both power and signal (high and low

voltage) uses. In fire incident data bases, these wire and cable products are usually classed as 'fixed wiring' since they are a permanent part of the building. [We do not include appliance cords, extension cords, or wires within other products, as these are evaluated as part of the electrical appliance.]

11.2 Application of the Methodology to Wire and Cable Products

11.2.1 Background

In general, wire and cable can represent both a fire ignition source (normally only power cables carry sufficient energy to ignite) and a fuel, as most insulation systems are combustible to a degree. Two wire insulation materials which have received attention in recent years are polyvinylchloride (PVC) for its release of HCl and polytetrafluoroethylene (PTFE) for its apparently high toxic potency. In each case, subsequent studies [295] and [296] of these materials in their actual context of use indicated that the perceived hazard may have been overstated.

Like the foam in aircraft seats, wire and cable are normally protected by a 'blocking layer' in the form of the wall or ceiling finish product. This separates the wire and cable from a majority of the other fuels in the building for both fire spread from the wire and cable (should it ignite first) and to it (should the fire originate in another item). Additionally, many power wires (the only type which can represent an ignition source) are installed in metal conduit or raceways which afford further protection.

All fire tests currently applied to wire and cable products evaluate their performance when exposed directly to a fire source without any enclosing media. Thus by themselves, these tests may not properly define the hazards of wire and cable in the context in which they are used, since the fire hazards of any product are highly coupled to its environment.

It should now be possible to ascertain the actual performance of products, such as cables, in the context of use. In order to demonstrate this, we must enumerate a set of scenarios which would cover much of the installed base. We then must quantify the fire hazards of wire and cable products, accounting for the specific contexts in which the products are used. It includes both power and signaling applications for a broad range of 'fixed wiring system' product constructions and occupancies.

An analysis should consider (a) fires originating in the wire or cable and spreading to other items, and (b) fires originating in other items which might eventually involve the wire and cable. For fires originating in the product, such ignitions would be presumed since modeling the ignition mechanisms is currently beyond the state-of-the-art.

We can then quantify the contribution of the wire and cable relative to the contribution of other burning items in each case. Based on this, a study could estimate the critical performance level of wire and cable products at which their contribution to the predicted hazard might be considered insignificant. To understand this role requires an integrated approach where:

- the fire performance properties of the product are ascertained through appropriate bench-scale measurement methods,

- the contribution of the product is determined through computational studies for a range of applications in which it is typically used, and
- the validity of the predictions is confirmed through well-designed real-scale testing.

The first aspect is the definition of scenarios of interest. The second would be the actual hazard calculation. The third would need to be full scale validation of the computational results.

11.2.2 Summary of the Current Study

A catalog of wire and cable products and the occupancies/applications in which they are normally found has been prepared with the assistance of industry experts, Table 3. This catalog will assure that all important contexts of product use are covered by the analyses that are developed in the project.

A bibliography of the fire literature has been compiled which reflects the state-of-the-art in wire and cable flammability research. The literature has been critically reviewed and summarized as to its potential contribution to the goals of this project. The review of the current test methods is particularly detailed, including summaries of each method and a critique of the method's design in light of current knowledge of fire science and metrology. The most appropriate methods for use in a performance based fire hazard assessment method for wire and cable products are specifically identified with such judgments technically justified.

11.2.3 What is Lacking

It has been pointed out that the data necessary for a hazard analysis can be obtained from fairly inexpensive small-scale testing of selected wire and cable products using methods such as the Cone Calorimeter (ASTM E 1354) and the NBS Toxicity Protocol [297]. Information by which to characterize the application environment is typically available through general statistical sources. There are two components missing, however. The first is the necessity of showing the verisimilitude between the results obtained from small scale tests, combined with the computational hazard analysis, and the real scale results that would be obtained in the context of use. In order to carry out such an analysis completely, there is one computational piece missing, a self-consistent pyrolysis model.

The Hazard Methodology, and indeed all models of fire growth, rely on what is commonly called a specified fire. In this application, one measures the heat release rate, smoke production, toxicity and so on with the test methods described above. Then these results are used to describe the fire which is used for the scenario calculations. In most cases this is an acceptable solution. The heat release and species production are constrained by the available oxygen. In general, but not always, such an analysis will yield a conservative result. The reason is that in reality, the amount of pyrolysate available is a coupled function of the heat generated, so often the mass flux from the fire will be different than expected from the tests performed in a free burn environment as is the case for the Cone Calorimeter and most other test apparatuses. Thus we can bracket the level of hazard, but for wire and cable in context, a flame spread model is essential. This would allow us to predict the results from most of the other purported

standards. For example, once the flame spread model has been bench-marked against full scale tests, it would be reasonable to predict the results from a test such as the UL 1666. Others, such as IEEE 383 require circuit continuity as the criterion and since there is no structural information in the fire models, this would be beyond the scope of use.

11.3 Scenarios

Scenarios are simply the classification of product and use on which a test is performed, in this case a numerical test. These should reflect the real world installation of products as a basis for the data used for the model calculations. Once these are enumerated and the results of the model run analyzed, product changes can be examined with relative ease. It is also easier to change, and observe change in, the world of the model than to do similar measurements in actual cases. This would allow 1) a reality check on the standard test methods discussed earlier, and 2) relative ease in obtaining results for new products and calculating the relative risk that they pose.

11.3.1 Definition of a Scenario

A general definition of a hazard scenario involves the specification of the in situ configuration of the product of interest, the cause of ignition, and in the case for which people are involved, the configuration of the building, along with time sensitive information (day, night, ...). It is also necessary to indicate whether or not secondary sources might be important. Normally, single sources are involved, but if secondary sources are to be considered, more detailed geometric information needs to be assembled. It should be pointed out that such considerations are well beyond any except the most ambitious **real-scale** experiments. The point of origin of the fire must be specified as well as the fuel area, and orientation of the item under consideration.

In some cases these choices are dictated by the desire to examine the results in terms of actual fires [298]. In general, though, the intended use of new products is the driving force for scenario specification.

11.3.2 Scenarios Applicable to Wire and Cable Products

The 'building' or in situ specifications apply to four types: residential, industrial, commercial, and ships. The product specifications are for concealed combustibles (within structural cavities), and both vertical and horizontal cable tray assemblies. We will deal only with fixed wiring in these discussions. Since we are trying to span the gamut of applications, a wide range of products can be specified from the newer types of low smoke and halogen free cables to the most common PVC or PE jacketed cables. Typical materials would be those that insulate power cables.

Four scenarios of particular interest are 1) building wire and cable in concealed spaces in residential settings, 2) power cables in vertical and horizontal cable trays in industrial buildings, 3) elevated cable bundles in ships and 4) cable runs in plenums in commercial buildings. For each of these, a range of cable types should be used to establish what is acceptable under current practice. In the four cases, it is very important that the context of use be defined. In some cases, the product will not present a problem

under any conditions. In other contexts, the cable may be bad in its own right, but the resultant hazard be the same whether or not the cable was present. That is, it may make no difference. Section 1.2.1 cited such an example. In general, based on the fact that most wire and cable is installed in protected spaces, one might expect to find that wire and cable products:

- are late to become involved due to their protected location,
- contribute little energy, smoke, and gas (as compared to other available fuel items) due to the performance of their materials of construction,
- contribute negligibly to fire propagation due to their performance and installation.

There are three small scale tests that need to be performed for each cable material. These are needed to obtain nominal heat release rates, later flame spread properties, and particulate production. Also needed are the results of the toxicity screening protocol (see below), so that it is known whether the product can be treated as an ordinary product, or must be evaluated as a separate entity (see the earlier discussion on toxicity of multiple burning objects).

11.3.3 Toxicity Protocol

It has been established that a very simple screening procedure can quantify whether a product behaves as a normal product, or as a particularly offensive product [297]. In general, a product can be screened to determine its LC50 value. Since all products produce some carbon monoxide, the largest (safest) value is determined by the most common product found in nature, namely wood.

Wood and all other similar products are assigned the value of 8 g/m³. Any product whose value is larger than 8 is arbitrarily assigned this value and treated as an ordinary product. In that case, it is solely the context of use which is important, and the relative fuel loading of the product of interest (cable in this case) to any other product. If the LC50 is smaller, then that value is assigned, and the product must be tracked individually as was discussed in the introduction. In this latter situation, the definition of a scenario might need to include probable locations of people, at least for commercial and residential occupancies.

11.4 Analysis of the Scenarios

The result of such a test procedure should be a clear understanding of the role of wire and cable products in building fires which will allow code bodies to pursue realistic regulatory actions for this class of products. By identifying when and under what specific conditions wire and cable might begin to contribute to the hazard, code authorities will have a better foundation on which to base appropriate regulation. By showing the relative contribution of a particular product to the overall hazard, it is possible to make a more realistic assessment of the necessity for regulation.

The assessment of the four scenarios can be divided by whether the fire is important, or the flame spread is important. For all four, the material properties as obtained by the small scale tests would be needed. For the former cases, the Hazard Methodology could then be applied immediately. For the latter, some

additional work would be needed to incorporate a flame spread model. But once this was done, the same analysis could be done. As an example, wire in a concealed space could be done as a specified fire. A fire ignited from within a cable, which is laying and densely packed tray covered with dust, would most likely have to be done with a flame spread model. The scenarios should be enhanced by use of a wide range of products. For example, in the case of concealed wiring, there are many sizes and uses. These necessitate various products. The cable used in the lavatory of an aircraft is considerably different from that used in normal residential wiring.

The outcome will be a statement of whether the products under consideration constitute a threat above and beyond the impact of other fuel loading. Further analysis will ascertain whether detection and/or intervention strategies can ameliorate the hazard.

Table 3. Catalog of wire and cable applications

Generic Type	Materials	Occupancy	Location	NEC Code
Fixture Wire	TP,TS,FEP	All Types	Lighting Fixtures & Connections	402
Machine Tool Wire	TP	Industrial/Commercial	Industrial Machinery	670
Pump Cable	TP,TS	Residential,Agricultural	Pump Control Panel & Casings	547
Switchboard	TS	All but Residential	Dedicated Location	384
Power Limited Circuit Cable	TP,TS,AP,FEP,ETFE	All Types	Ducts,Plenums,Air Handling Spaces,Raceway,Riser,Non-Plenum	Cable Tray 725
Armored Cable	TP,TS	All Types	Exposed & Concealed Work,Tray	333
Non-metallic Sheath	TP	All except as Restricted	Exposed & Concealed	336/337
Service Entrance	TP,TS	All	Exposed & Concealed	338
Thermoplastic Building Wire	TP	All	Exposed & Concealed	310
Thermoset Building Wire	TS	All	Exposed & Concealed	310
Underground Feeder	TP,TS	All	Exposed & Concealed	339
Underground Service Entrance	TP,TS	All	Exposed & Concealed	338
Metal Clad Cable	TP,TS	All	Exposed & Concealed,Tray	334
Power and Control Tray Cable	TP,TS,PTFE,ETFE	All but Residential	Cable Tray,Raceway	340
Ltd. Energy Fire Prot. Cable	TP,TS,AP,FEP,ETFE	All but Residential	Ducts,Plenums,Air Handling Spaces Raceway,Riser,Non-Plenum	760
Thermostat Wire	TP	All	Tray,Raceway,Exposed Concealed	
Flexible Cord	TP,TS,TPE	Appliances, Stage Lighting Data Processing Equipment	Exposed	400
Elevator Cable	TP,TS	All but Residential	Elevators/Dumbwaiters	620
Instrument Control Cable	TP,TS	Process Control,Data Process	Tray,Raceway	340
Mineral-Insulated Metal Sheath	MgO	All	Exposed & Concealed	330
Thermoplastic Power Cable MV	TP	Industrial,Commercial	Tray,Raceway	326

Generic Type	Materials	Occupancy	Location	NEC Code
Thermoset Power Cable MV	TS, TP	Industrial, Commercial	Tray, Raceway	326
Thermoplastic Communication Cable	TP	Gen. Purpose Communication	Ducts, Plenums, Air Handling Spaces Raceway, Riser, Non-Plenum	800, 770
Station Wire	TP	Limited Use Communication	Ducts, Plenums, Air Handling Spaces Raceway, Riser, Non-Plenum	800
Undercarpet Cable	TP, TS	All but Residential Schools, Hospitals	Under Carpet Squares	328

KEY

TP Thermoplastic
TS Thermoset
FEP Fluorinated Ethylene Propylene
AP Aromatic Polyamide
ETFE Modified Ethylene Tetrafluoro-Ethylene
TPE Thermoplastic Elastomer
MgO Magnesium Oxide

12 Conclusions

12.1 Standards/Test Methods

From a fire engineering point of view, optimal flammability test methods would comprise the following minimum set:

- (A) A real-scale, benchmark test, wherein at least heat release rate (HRR) and smoke production are accurately determined. The fire scenario [=ignition source] would be agreed upon as being the most suitable for the given task. The test article would be installed in a real-scale test environment, not merely in a test rig which is somewhat large, but insufficiently so to qualify as a real-scale environment.
- (B) An accompanying bench-scale technique for HRR and smoke measurement. The bench-scale technique would have been sufficiently validated against the real-scale results. This method would be the common, every day test used for obtaining flammability data on wire and cable products. However, in practice, there could remain certain application areas where only real-scale testing would be permitted.

Such an ultimate pair of tests has not yet been achieved, although recent research in this area has been very encouraging. The large-scale measurement technology used at UL for wire and cable products has been making very substantive advances in this direction, however. Progress in the area of international standards and of test methods issued by other North American organizations has been less rapid. Those U.S.-origin standards which represent substantive progress over the technology represented in the current international IEC standards should be proposed to that body for its consideration. Detailed findings concerning both UL tests and those of other organizations are summarized below.

The U.S. requirements for wire and cable flammability are primarily expressed through NEC provisions. The provisions have generally been created without the benefit of systematic, quantitative study of real fires, which would then have led to rationally based, consistent provisions. Canadian test philosophy has had a significant influence on the course of development of the U.S. standards. Methods from other countries and from IEC have had only very limited influence on U.S. testing practice. In more detail, we summarize the following points:

- The NEC requirements should be re-examined *in toto* to develop a consistent set of requirements which can be quantitatively justified on the basis of validation against real-scale fires. Excessively conservative provisions which cannot be justified on such a basis should be removed.
- The IEEE 383 and most other currently used reaction-to-fire tests for wire and cable determine either maximum flame travel or maximum damage length as the primary variable reported. The findings are then interpreted in a simple pass/fail way. This pass/fail rating procedure does **not** segregate products into 'hazardous' versus 'non-hazardous' ones. Instead, the passing specimens merely propagate less than the failing specimens. This has been recognized for some time (*e.g.*, [20],[299]), but without specific action being taken.

- The current knowledge of fire protection engineering indicates that the main variable to be measured should be heat release rate (HRR), not flame travel or length damage. Fire tests should be made consistent with this fact. By use of HRR measurements it is possible to compute the expected hazards from fires quantitatively. The provisions of the NEC should reflect this knowledge.
- Bench-scale HRR testing is being adopted by the fire protection engineering community for characterizing fire hazards of numerous products. Exploratory testing programs have indicated that this is both viable and preferred for the testing of electric cables. Such methods should be further explored, with a goal of standardizing procedures.
- When smoke hazard needs to be characterized, the measurements should be made in appropriate test apparatuses and using measuring techniques that enable quantitative data to be obtained which are consistent with the needs of engineering computations.
- Current fire engineering state-of-the art suggests that, in general, two types of tests are needed: real-scale fire tests and bench-scale fire tests. The former must, by their design, capture all the important features of actual fire conditions. The latter must, to be usable, be validated against appropriate real-scale tests.
- The IEEE 383 test (also IEEE 1202, UL 1581, and UL 1685) is an intermediate-scale test. As a result, if it is to be retained, validation results against real-scale fire should be demanded. While some anecdotal references to the performance of this test in predicting real-scale fires may be available, we find no record of a systematic validation effort. As a minimum, we see such a validation as requisite. A better strategy, however, is to move over to the use of bench-scale HRR testing, in preference to this intermediate-scale test.
- It has been shown that the results of UL 1581/IEEE 383 testing can be predicted by use of bench-scale HRR data. As an interim step, conversion of IEEE 383 and related tests to measuring HRR should be considered; this has already been implemented by Underwriters Laboratories as an optional portion of their UL 1685 test.
- The effects of varying the ignition source either in the real fire or in a intermediate-scale rig such as the IEEE 383 are not well-known. We find it troubling, however, that investigators who studied vertical cable trays conducted at various burner power levels have all recommended that the 21 kW level is too low. A comprehensive experimental program should be launched to quantify our knowledge in this area. This should be accompanied by a loss study program to determine the appropriate ignition sources identified with various building categories and fire scenarios. The latter is important since the existing cable tests have been developed without such a factual basis.
- The smoke measuring procedures devised for UL 1685 are sensible and sound and represent one of the few instances so far where rational engineering units and computational smoke procedures have been introduced. The optional HRR measuring component of the test is also entirely consistent with current engineering state of the art.
- The UL 1666 riser test is of actual fire scale and represents a reasonable fire source and scenario. Bench-scale methods be developed which successfully predict its results.

- The UL 910 test presents unjustifiably severe and anomalous performance demands on plenum cables. A validation effort *has* been made for UL 910 and demonstrated that the requirements are unrealistic and do not reflect actual plenum fire behavior. In addition to failing the validation effort, this test presents some fundamental problems from the point of view of test design. To wit, the severity of this test does not conform to normal engineering practice for building fire resistance requirements. Almost all building codes require significantly greater resistance against fire propagating floor-to-floor than they do for fire propagating horizontally within a single floor. Here, instead, the UL 910 horizontal-spread test is much more severe than the UL 1666 test used to assure that fire does not propagate along cabling floor-to-floor. This situation should be corrected by relaxing the UL 910 requirements sufficiently so that validation becomes successful, then examining the positioning of UL 910 against UL 1666.
- Larger-scale Canadian CSA tests for cables are very similar to U.S. tests and differ only in details. Both the new IEEE 1202 method and the CSA variant of UL 1685 serve to bring U.S. and Canadian standards closer together in this area.
- The new IEEE 1202 test addresses a number of the deficiencies noted with IEEE 383. By means of changed burner orientation and changed instructions for tray packing it successfully increases the severity of the test. However, the question as to whether a 62 kW (or similar) exposure is to be preferred remains unanswered. Also lacking is validation of the results of this intermediate-scale test to actual performance.
- The '3 metre cube' test for smoke is very widely used in Europe and has become an IEC standard (IEC 1034). Both the representation of fire conditions and the measurement of smoke, however, are very primitive in this test. For smoke measurement on larger-size specimens, the procedures incorporated into UL 1685 are more sound and are to be preferred. In the longer term, it should prove not necessary to make any smoke measurements in large rigs, as bench-scale data can be expected to become fully correlated.
- The only two international standards in common use that use an intermediate-scale (or large) test environment are IEC 332 Part 3 and IEC 1034. Conceptually, the IEC 332 Part 3 test is very similar to IEEE 1202, although test details are different and data are not interchangeable. There are no international standards which use a real-scale fire environment (such as exists in UL 1666) or a smoke measurement system that can provide data in suitable form for use in engineering computations (as is available from UL 1685).
- Data from small burner (Bunsen, Tirrill, etc.) test methods do not have a significant role in engineering analysis of fire hazards. The tests are intrinsically pass/fail and do not provide quantitative data which would be useful in analysis. They are appropriately used only when a minimal assurance against very-readily ignitable materials or products is needed.
- Enough comparative data is not available to directly compare the quality of the various small burner test methods. Part of such a comparison would require assessment of the reproducibility of their results. Unfortunately, most of these test methods have been developed in quite an *ad hoc* manner without a great deal of regard for procedures to ensure the reproducibility of their results. The working draft for the proposed international standard IEC 695 Part 2-4 Sheet 0 contains the major engineering principles required to remedy this situation. Consideration should be given to updating North American standards to make them consistent with these recommendations.

- The objective of maintaining communications, control and other circuits during the course of a fire is a reasonable one. This may be achieved by means of redundant circuits separated by barriers or routed through areas rated for fire resistance, or by cables designed to operate in high temperature environments. Passing results obtained with current, international circuit integrity tests may mislead designers and result in inadequate performance during real fires unless more realistic exposure conditions are utilized.
- The FMRC cable flammability standard is based on highly peculiar bench-scale test conditions which do not correspond to those of the end-use environment. The amount of larger-scale validation data offered is not sufficient to inspire confidence with the method. An objective of establishing several rating classes (instead of a single pass/fail criterion) can be readily achieved by the types of HRR-based instrumentation incorporated into the UL 1685 test. Bench-scale alternatives should not be used unless the test conditions are well-related to the end-use environment and the test results are sufficiently well-validated against real-scale fires.
- The NES tests for smoke and corrosivity/toxicity are based on seriously outmoded testing technology. Their use should be discontinued in U.S. military specifications.
- Accurate estimates of actual fire heat release rates can only be made once a model for flame coverage is available. Work should be started on such a model for cable fires, to be generalized from the existing study of Göransson and Wickström.
- An experimental program should be defined to determine if plaque testing is a viable bench-scale HRR testing alternative to testing of actual, fully-made-up cable specimens. If successful, such a testing method could have significant impact on reducing the costs of development work on new polymer formulations.
- Existing models for the fire behavior of wire and cable products are not able to address normal engineering needs. New fire models in this area will also require that real-scale experimental studies be conducted upon which to base the modeling effort.

12.2 Directions for the Future

This comprehensive review of the state of knowledge concerning the fire performance of wire and cable has demonstrated a number of unarguable facts about current testing procedures:

- There are numerous tests in use which do not hold up under the scrutiny of current fire science and should be abandoned.
- Many tests are sufficiently similar to others that they could be merged into a common procedure while at the same time, improvements in instrumentation and procedural specification are made to improve reproducibility and to extract more data.
- Eventually, all tests must result in data which supports fire hazard and fire risk assessment methods. The world's fire science and engineering community is clearly moving in this direction. This will likely mean a migration to HRR type testing.

- Where classification tests are retained (i.e., where the classification cannot be made on the basis of data from other test methods), the testing conditions must be justified relative to product exposure in its context of use.
- In all cases, real-scale validation of test methods must be carried out to insure that test conditions are neither too lenient nor too severe. Prior experience with the influence of major variables (as have been detailed in this report) should be taken into account in designing such tests.
- Research necessary to integrate flame spread prediction over wire and cable products must be expedited in order to be able to analyze the role of wire and cable flammability with fire models. The theoretical basis for these models is in place, and their practicability has been demonstrated.
- A decade of research on combustion toxicity has resulted in sufficient understanding to classify products into *ordinary* and those that require special treatment. Most wire and cable products, including those about which there was significant prior debate, have been shown to lie in the ordinary class. The potential exists for similar hasty judgements to be made with regard to corrosivity. As a minimum, the similarity of the two topics should be exploited.

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U.S. and Canadian reaction-to-fire tests for wire and cable are examined. The technical basis for their development is analyzed. The data requirements for engineering computations of fire hazard are examined. It is found that the current methods are primarily based on determining ignitability, speed of flame travel, or distance of flame propagation. The fire hazard to building occupants, however, is associated with the heat release rate of the fire, instead. Newer testing methods, which are not yet standards but which do measure the heat release rate of cables, are already under development. A limited comparison is made to British and international standards. Recommendations are made for improved testing strategies. The document includes about 300 references.

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